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THERMODYNAMICS OF ROCKET PROPULSION AND THEORETICAL EVALUATION OF SOME PROTOTYPE PROPELLANT COMBINATIONS

by
Thomas O. Dobbins, 1/Lt USAF

Propulsion Laboratory

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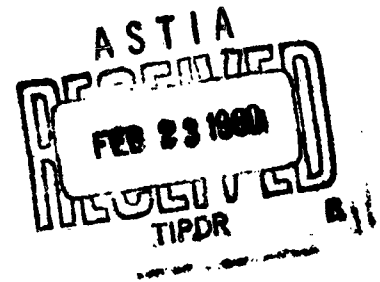
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WRIGHT AIR DEVELOPMENT CENTER
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by 1/Lt Thomas O. Dobbins of the Rocket Propellant Section, Fuels and Oils Branch, Propulsion Sub-Systems Division, Propulsion Laboratory. Work was performed under Project 3148, "Development of Liquid and Solid Rocket Propellants". This work was also submitted by the author as a thesis for the degree Master of Science at the Ohio State University, December 1959.

ABSTRACT

↓

This report presents a concise summary of the thermodynamics of rocket propulsion and the evaluation of 100 prototype propellant combinations. Emphasis is placed on the thermodynamics of chemical propulsion and on flow through the converging-diverging nozzle. From this basic theory, two (2) rigorous methods are developed for conducting theoretical performance calculations. One (1) of these utilizes thermodynamic equilibrium constants while the second utilizes a completely new concept of minimizing the total free energy of the combustion products. Sample calculations are presented for each method. Thermodynamic data are presented and discussed for several reactants and all important products of combustion consisting of the elements carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, lithium, boron, beryllium, aluminum, and magnesium. A rigorous theoretical evaluation is presented for 100 prototype propellant systems. Specific impulse, chamber temperature, exhaust temperature, characteristic exhaust velocity, and chamber molecular weight are plotted as a function of the propellant composition. Also, complete performance data are tabulated for selected fuel-to-oxidizer ratios.

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PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

C. L. Word

C. L. WORD
Chief, Propulsion Sub-Systems Division
Propulsion Laboratory

PREFACE

In this report, the author has attempted to present a concise, comprehensive, fundamental approach to the theoretical evaluation of rocket propellant performance. First, those basic principles of thermodynamics and fluid dynamics directly related to rocket propulsion are reviewed. Although many detailed textbooks have been prepared on these two subjects, fewer attempts have been made to combine the phases applicable to rocketry into one summary. From this fundamental theory, two rigorous methods of calculating propellant performance are presented.

One of these approaches, the minimization-of-free energy at constant enthalpy or constant entropy, has not been published previously. Then, using the latter method of calculation, the author has evaluated the performance of a series of prototype fuels and oxidizers. The basic thermodynamic data used in this evaluation are also presented and discussed.

Many scientists have contributed indirectly to this report by their work in the basic areas of thermodynamics, fluid dynamics and propulsion. Unfortunately, there is no adequate way to repay this debt except through a general acknowledgement. When material has been taken from the publications of others, this has been indicated by footnotes in the text. The author's first specific acknowledgement is to Professor P. R. Jones of West Virginia University and Dr. W. B. Kay of the Ohio State University who introduced him to the science of thermodynamics and kindled his interest in the subject. Furthermore, an additional acknowledgement is made to Dr. Kay for his guidance and interest while serving as adviser to the author on this project. Also, Dr. R. S. Brodkey of the Ohio State University is

recognized for his inspiring teaching of fluid dynamics.

Substantial assistance was provided by several others in preparing specific sections of this report. The author wishes to acknowledge Mr. A. E. Roberts, Jr. of General Kinetics, Inc. who programmed the minimization-of-free energy concept for the Universal Scientific Computer, Model 1103A, and who offered valuable constructive comments on the author's presentation of this theory. Thanks are also due Mr. L. J. Gordon of the Aerojet-General Corporation for his guidance in evaluating the relative importance of propellant density and specific impulse. The author is grateful to Dr. C. B. Henderson and Mr. R. S. Scheffee of the Atlantic Research Corporation for their valuable assistance in assembling thermodynamic data on reactants and products-of-combustion. Additional recognition is given to Dr. D. R. Stull of Dow Chemical Company, Mr. John S. Gordon of Reaction Motors Division of Thiokol Chemical Company, and to Dr. Charles W. Beckett, Inc., and his colleagues at the National Bureau of Standards for their assistance and advice in obtaining accurate thermodynamic data. The unpublished multiphase flow theory of Dr. David Altman of United Aircraft Research also contributes to the comprehensiveness of this report. The interest of each of these gentlemen is sincerely appreciated.

Finally, but certainly not least, thanks are due to Miss Dora M. Wolfe and Mrs. Laveria Howard of Wright Air Development Center for typing the text of this report, and to Mr. Nicholas Engler and Mr. William Powers of the University of Dayton for assisting with the plotting of graphs.

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CHAPTER I

INTRODUCTION

A. Historical Background

Although the concept of rocket propulsion is an old one, in practice it is a relatively new aeronautical science. Professor Robert H. Goddard, hailed as the father of American rocketry, began his studies in the year 1915.¹ For the next 25 years, he and his followers pioneered rocket research within the United States until the outbreak of World War II stimulated considerable interest in their activities. Since that time, rocket research and development has been pursued at an accelerating rate until it now constitutes a significant part of the activity of America's aircraft industry.

From the time of Goddard's early experiments, rocket scientists have needed to know the performance of a rocket propellant system before designing a missile to use it. Originally, thermodynamicists theoretically calculated the performance of a few carbon-hydrogen-oxygen propellants by hand. However, the complexity of the calculation coupled with the lack of high temperature thermodynamic data limited their activity. As some rocket thermodynamicists attempted to expand the scope of their work, short-cut methods of calculation were developed. However, these techniques invoked simplifying assumptions which introduced considerable error as the chemical complexity of the propellants increased, particularly if condensed phases were formed as products of combustion.

In the early 1950's, investigators at the Lewis Laboratories of the National Advisory Committee for Aeronautics developed a program for calculating the performance of propellants composed of carbon, hydrogen, oxygen, nitrogen, chlorine, and fluorine on the IBM 650 digital computer. Similarly, investigators at California Institute of Technology's Jet Propulsion Laboratory programmed the Datatron 201 computer. This constituted an advancement in theoretical analysis work. However, these and many similar programs subsequently developed by others have been designed to evaluate specific ingredient elements which form specific products of combustion. In these cases, neither new ingredient elements nor new products of combustion may be considered without re-writing the computer program. Furthermore, the shortage of memory capacity in small and medium-size digital computers has limited the complexity of the propellant system which could be evaluated.

As an extension and expansion of this earlier performance calculation work, a completely general computer program based upon a new concept of the minimization of free energy has been established at Wright Air Development Center. This program, prepared for the Universal Scientific Computer, Model 1103A, is neither limited by the number or type of elemental ingredients nor by the number or state of the products of combustion. For all practical purposes, any propellant system for which thermodynamic data are available may be evaluated. This achievement may be considered a logical outgrowth of the work of earlier investigators.

B. Object and Scope

This report has been prepared as a contribution to the theoretical evaluation of potential fuels and oxidizers as propulsion media. The object

of the report is to present the thermodynamics of rocket propulsion and the evaluation of several prototype propellant combinations. The scope may be divided into four logical areas: (1) a concise, comprehensive treatment of the fundamental theory of rocket propulsion; (2) a detailed description of two rigorous methods for calculating propellant performance; (3) a discussion of the thermodynamic data for a number of selected reactants and products of combustion; and (4) the evaluation of the performance of several prototype propellant systems.

The development of fundamental theory is designed to incorporate all important concepts into one logical, comprehensive summary. The literature has been carefully screened in order to utilize the contributions of previous workers. Emphasis is placed on the thermodynamics of chemical propulsion and on flow through the converging-diverging nozzle. From this basic theory, two rigorous methods are developed for conducting theoretical performance calculations. One of these utilizes thermodynamic equilibrium constants to express the concentrations of minor products of combustion in terms of the major species. The second method utilizes a completely new concept of minimizing the total free energy of the combustion products. Although both methods are equally rigorous, the latter one is more general and was applied to the calculational work.

Thermodynamic data are presented and discussed for several reactants and all important products of combustion consisting of the elements carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, lithium, boron, beryllium, aluminum, and magnesium. Ten prototype fuels and ten prototype oxidizers were then chosen for rigorous theoretical evaluation. Although a number of

these systems do not constitute workable propellant combinations, they were selected because of the basic combustion information which could be obtained. The study was designed to reveal the relative merits of various elements and chemical bonds as ingredients for chemical propellants. In conducting the calculations, all known products of combustion were assumed to exist. Since the calculational technique was completely rigorous, the accuracy of the calculations in this report is limited only by the accuracy of the basic thermodynamic data used. Therefore, this report is submitted as a comprehensive resume' of the present state-of-the-art in theoretical propellant evaluation.

CHAPTER II

SUMMARY

The evaluation of chemical rocket propellants may be based directly upon the laws of thermodynamics. The energy available from any chemical propellant combination is directly proportional to the square root of the change in enthalpy of the system as it flows through a converging-diverging nozzle. This analysis is equally applicable to both compressible and multiphase flow. In the latter situation, thermal and momentum equilibrium between the gas phase and the condensed phase are very closely approached when the diameter of the condensed particle is less than ten microns. If this size is exceeded, the momentum lag may cause a loss of useful energy. Although the density of a propellant combination must be considered in evaluating its effectiveness in a given missile application, the specific impulse is the most significant parameter in screening propellants.

Rigorous performance calculations must be made by assuming adiabatic combustion in the chamber and isentropic expansion through the nozzle. This may be accomplished by either the method of equilibrium constants or the method of minimization-of-free energy. The latter is recommended for conducting calculations on a high-speed digital computer because of its completely general approach.

High temperature thermodynamic data are available for the products of combustion of most of the interesting propellant ingredients. However, in many cases these data are extrapolated from experimental studies at

lower temperatures. Therefore, additional experimental studies are needed to refine the thermodynamic properties of many substances. This is particularly true of the compounds of the light metals lithium, aluminum, beryllium, boron, and magnesium.

Fluorine and oxygen difluoride were found to be excellent oxidizers for most of the prototype fuels studied. Hydrogen and beryllium hydride were universally energetic fuels. For oxidizers, the O-F bond was found more energetic than the H-F bond which, in turn, surpassed the Cl-F bond. For fuels, hydrogen was found to be an essential ingredient for high energy. Nitrogen appears more desirable than carbon as a carrier element. Beryllium appears to be the most promising of the light metals, although boron and aluminum offer considerable energy. Lithium is considerably more energetic if oxidized with fluorine than if oxidized with oxygen.

CHAPTER III

FUNDAMENTAL THEORY OF ROCKET PROPULSION

A. Rocket Propulsion Principles

1. General Principles

All known methods for propelling a body through a fluid medium are based upon the reaction principle. One of these methods is rocket propulsion, which may be defined as a means of locomotion through which reaction is imparted to a vehicle by the momentum of ejected matter.² The matter is ejected as a high-speed gas stream, which is generated by chemical reaction between a fuel and an oxidizer stored within the vehicle. By accelerating the gas stream through a converging-diverging nozzle, supersonic velocities are attained. Thus, rocket propulsion is achieved by the conversion of the thermal energy of a chemical reaction into the translational energy of the products of combustion.

The theory of propulsion was first presented by Sir Isaac Newton in the year 1686 with the publication of his three fundamental laws of motion in Philosophiae Naturalis Principia Mathematica. These laws state that: (1) every body tends to continue either in a state of rest or in a state of uniform motion unless acted upon by external forces; (2) a change of motion is proportional to the force introducing the change and occurs in a straight line along which the force acts; and (3) the action of a force is always opposed by an equal and opposite reaction. Newton's second law of motion constitutes the fundamental principle of fluid dynamics. Combining the second and third laws, the magnitude and direction of all momentum changes are defined.

In addition to Newton's laws, the behavior of compressible fluids is also governed by the law of conservation of mass, the first law of thermodynamics, and the second law of thermodynamics. These laws are completely independent of the nature of the propelling medium. For a specific rocket propulsion process, additional subsidiary laws may be introduced which are related to the particular nature of the propelling medium. These include the equation of state and equations expressing the thermodynamic properties of the fluid.

2. The Momentum Principle

From the laws of motion, momentum is shown to be a vector quantity possessing the direction of the velocity vector. The time rate of change of the total momentum of a bounded body of fluid is equal to the resultant of the external forces acting on the boundaries, i.e.

$$\Sigma F' = \frac{d}{dt} (mv) \quad (1)$$

The net external force is also a vector quantity having the same magnitude and direction as the velocity vector representing the change in the rate of momentum.

In applying the principle of momentum to rocket propulsion, another term must be added to the momentum equation when a difference in pressure exists between the emergent fluid jet and the surrounding fluid medium. Thus, the total thrust imparted to a vehicle moving through a homogeneous external fluid is composed of the momentum thrust and the pressure thrust. The former is the product of the mass flow rate of propellant and the exhaust velocity of the emergent fluid stream relative to the vehicle. The latter is the product of the cross-sectional

area of the emergent stream and the difference in pressure between this stream and the surrounding medium. Mathematically,

$$F' = \frac{m}{g} v_e + (p_e - p_a) A_e \quad (2)$$

where

- F' = thrust
- m = mass flow rate
- g = acceleration of gravity
- v_e = velocity of exhaust gases at nozzle exit
- p_e = nozzle exit pressure
- p_a = external surrounding pressure
- A_e = exit area of nozzle

When the exhaust pressure is exactly equal to the pressure of the external fluid medium, the pressure thrust term becomes zero. This condition defines the optimum thrust obtainable from isentropic flow through a converging-diverging nozzle, and will be discussed in more detail in a subsequent section. When the nozzle exit pressure exceeds the external pressure, the nozzle area is not sufficiently large to permit complete expansion of the working fluid. On the other hand, if the exhaust gases are overexpanded to a pressure less than the external pressure, a shock wave will occur in the nozzle. Thus, either over-expansion or underexpansion induces a loss of energy and a corresponding reduction in the exhaust velocity.

Actually, only the axial component of velocity will produce a net thrust in a converging-diverging nozzle. Therefore, in comparing experimental and theoretical thrust values, a geometric correction must be applied, i.e.

$$F' = \frac{1}{2g} (1 + \cos \alpha) m v_e + (p_e - p_a) A_e \quad (3)$$

where α is the half angle of nozzle divergence. Thus, the effective exhaust velocity for the general case is defined as

$$v' = \frac{F'g}{\dot{m}} = \frac{1}{2} (1 + \cos \alpha) v_e + \frac{(P_e - P_a) A_e}{\dot{m}} \quad (4)$$

This, in turn, leads to the definition of specific impulse, which is one of the most important parameters for evaluating rocket performance.

3. Useful Rocket Parameters

Specific impulse is defined as

$$I_{sp} = \frac{F'}{\dot{m}} = \frac{v'}{g} \quad (5)$$

or the pounds of thrust obtained per pound of propellant flow per second. In practice, the dimensions of specific impulse are reduced to seconds. It will be shown later that specific impulse is a property of the chemical composition of the propellant and can be theoretically evaluated by thermodynamic analysis.

In ordinary engineering practice, variations in gravity are unimportant, and mass and weight quantities are used interchangeably. Although the thrust of a rocket is actually a function of the mass flow rate (not of the weight flow rate), weight terminology is still preferred for use by the rocket industry. Actually, specific impulse is independent of gravity and other external effects and, in mass terminology, would have the dimensions of ft/sec and be numerically equal to the effective exhaust velocity.³

In most experimental rocket motor tests, the following quantities are either measured or known:

- (1) Thrust, F'
- (2) Combustion pressure, p_c
- (3) Exit pressure, p_e
- (4) Nozzle throat area, A^*
- (5) Nozzle exit area, A_e
- (6) Mass rate of propellant flow, m
- (7) Propellant composition

The overall performance, as measured by specific impulse or exhaust velocity, is evaluated experimentally from items (1) and (6) or computed theoretically from items (2), (3), and (7). However, in some test work it is desirable to individually analyze the combustion and the expansion processes. The combustion process should determine the ability of a propellant combination to generate useful energy while the expansion process should determine the effectiveness of utilizing that energy. For this reason, two experimental quantities, the characteristic velocity and the nozzle thrust coefficient, are defined respectively as

$$c^* = \frac{p_c A^* g}{m} \quad (6)$$

and

$$C_F = \frac{F'}{p_c A^*} \quad (7)$$

The characteristic velocity is actually the velocity of sound at the nozzle throat. In essence, this is a measure of the effectiveness with which the combustion products are generated in the rocket chamber. Closely related to the characteristic velocity is the weight flow coefficient, or discharge coefficient, which is defined as

$$C_W = \frac{m}{p_c A^*} \quad (8)$$

This parameter gives a direct measure of the rate of consumption of the propellant. The product of the thrust coefficient and the characteristic velocity equals the exhaust velocity.

The total impulse may be expressed either as a function of thrust or of specific impulse:

$$I = F't = I_{sp} \cdot W_p \quad (9)$$

where

I	=	total impulse
t	=	operating time
W_p	=	total weight of propellant consumed
I_{sp}	=	specific impulse
F'	=	thrust

This is a measure of the total energy possessed by a given missile, and may consist of a large thrust lasting for a short duration or a smaller thrust acting for a longer time.

B. Analysis of the Ideal Rocket

1. Fundamental Technical Assumptions

The quantitative treatment of fluid dynamics may be based directly upon the laws of thermodynamics.⁴ A strictly thermodynamic approach does not require any consideration of the mechanism of flow. Rather, it constitutes an energy analysis and establishes the limiting, ideal conditions of flow. A frictionless, one-dimensional flow is assumed which is independent of fluid viscosity, the transport property of momentum. This approach is quite justified from an engineering viewpoint since the viscous forces are negligible compared to the inertial forces.

Frequently, the measured performance of rocket engines exceeds 95% of the ideal, theoretical values. Furthermore, the accepted practice for designing rocket engines is to utilize ideal rocket parameters and modify these by empirical corrections.

Before introducing the equations of thermodynamics which govern rocket propulsion, the assumptions invoked in analyzing the combustion and expansion processes will be discussed. The thermodynamic approach must possess a maximum sophistication in order to place the minimum amount of limitation upon the theoretical results. Therefore, assumptions are limited to those justified by theoretical or experimental evidence, those introducing a negligible effect on the final results, and those representing the ideal limit for chemical and physical phenomena which lack experimental verification. These assumptions are the following:

- (1) The gaseous species behave ideally, i.e. obey the perfect gas law.
- (2) Dalton's Law applies.
- (3) Molar enthalpies of all species are independent of pressure.
- (4) Molar entropies of condensed phases are independent of pressure.
- (5) Steady-state conditions exist during combustion and expansion.
- (6) Condensed phases occupy a negligible volume.
- (7) The entropy of mixing is negligible for condensed phases.
- (8) Vapor pressures of condensed phases are independent of total pressure.
- (9) The combustion process is adiabatic.

- (10) Combustion occurs at constant pressure.
- (11) Thermal and chemical equilibria exist in the combustion chamber.
- (12) Homogeneous mixing is attained.
- (13) The combustion products in the chamber have zero bulk velocity with respect to the walls of the chamber.
- (14) Isentropic, frictionless, one-dimensional flow occurs in the nozzle.
- (15) The exit velocity of the combustion products is uniform across any section normal to the nozzle axis.
- (16) The gases are insoluble in the condensed phase, and the condensed phases themselves are immiscible.
- (17) The particles are thermodynamically macroscopic.
- (18) Condensed phases are in thermal and velocity equilibrium with the gas stream during the expansion process.

2. Discussion of the Assumptions

The first five of these assumptions may be considered as justified by existing experimental evidence. The only questionable point appears to be the assumption of ideal behavior for the vapors of the metal oxides. Because of their high boiling points, these compounds could conceivably deviate somewhat from ideality at combustion conditions. However, the relatively small concentrations of these vapors in the combustion products will tend to minimize the significance of any possible non-ideal behavior. The ideal gas approximation has been found to be quite adequate for the more common combustion products.

Assumptions six, seven, and eight are made to simplify the calculation procedure. In these cases, correction is not particularly difficult, but the effect upon the final results is negligible.

Any error introduced by these assumptions is certainly insignificant compared to uncertainties in the basic high-temperature thermodynamic data themselves.

Assumptions nine through fifteen are peculiar to the rocket propulsion process itself, i.e., an adiabatic combustion followed by an isentropic expansion through a converging-diverging nozzle. These assumptions represent the ideal, limiting conditions of energy utilization and overall efficiency, and are approached experimentally in large rocket engines. In practice, the geometry of the rocket engine may affect the attainment of equilibrium. A short reaction chamber may not afford a sufficiently long residence time for some chemical reactions to reach equilibrium. In the nozzle, the attainment of equilibrium could conceivably be inhibited by the nature of the chemical reaction and the existing physical conditions. For example, associative reactions would be less likely at lower pressures when fragments would be more remote and their probability of collision relatively less. The one-dimensional flow approximation is an excellent one in short ducts of variable cross-sectional area. In this case, the fundamental cause for the change in flow conditions is the variation in the area, and other causes, such as boundary layer development and skin friction, have only a secondary influence.⁵ Changes in properties normal to the streamline are considered negligible compared to changes in the direction of flow. Hence, average properties over the cross-section are evaluated. Errors are minimized when the change in cross-sectional area per unit length is small, when the radius of curvature is large compared to the diameter, and when the shapes of the velocity and temperature profiles remain constant with length.⁶

Assumptions sixteen through eighteen represent ideal, limiting approximations for unproved physical and chemical phenomena. The questions of gas solubility in condensed species and of the miscibility of liquid phases are worthy of consideration. These phenomena could bear some significance, particularly for cases in which liquid metal oxides constitute a relatively large percentage of the total mass of combustion products. However, assumption eighteen is probably a greater potential source of error. The degree of thermal equilibrium between the gas and condensed phases is dependent upon the rate of heat transfer, while the degree of acceleration of the condensables by the gas is dependent upon the rate of momentum transfer. Both transfer rates are greatly affected by the particle sizes of the condensed phases. As the particle size of the condensable decreases, both thermal and momentum equilibrium are approached to a greater degree. Efforts have been made to predict the degree of approach to these equilibria by the use of empirical rate constants.^{7,8} The tentative conclusion of these studies was that both thermal and momentum equilibrium are very nearly approached in two-phase flow provided the particle diameter of the non-gaseous phase does not exceed ten microns.

The expansion process through the converging-diverging nozzle may be analyzed by four basic approaches. These are:

- (1) Shifting chemical equilibrium accompanied by complete phase equilibrium.
- (2) Shifting chemical equilibrium with frozen phase equilibrium.
- (3) Frozen chemical equilibrium with complete phase equilibrium, i.e. equilibrium condensation.
- (4) Frozen chemical equilibrium and frozen phase equilibrium.

The first basis is the most ideal one and establishes the maximum theoretical performance of a given propellant combination at an established set of operating conditions. On the other hand, the fourth basis represents the lower limit of performance. Experimental evidence indicates that the equilibrium conditions of the chamber are shifted to a certain degree during the expansion process. Only the degree of the shift is questionable, and this undoubtedly is dependent upon the particular propellant combination. Therefore, for practical purposes, if both the first and fourth approaches are evaluated, the theoretical performance may be "bracketed" by establishing its maximum and minimum limits.

3. Uncertainties in Performance Calculations

Practically all of the fundamental uncertainties related to theoretical performance calculations are concerned with the phenomenon of two-phase flow. Until more basic information is obtained on this phenomenon, theoretical performance calculations cannot be refined further. The particular problem areas related to rocket propulsion which are in need of more basic study include:⁹

- (1) The extent of approach to thermal equilibrium between the gaseous and condensed phases.
- (2) The extent to which the velocity of the condensed phases lags behind that of the gas phase.
- (3) The rate of formation and growth of the condensed particles.
- (4) The effect of miscibility of two or more condensed phases and the effect of solubility of the gas phase constituents in the condensed phase.
- (5) The degree of non-ideality of the vapors of condensed phases, particularly in the region of saturation conditions.

C. Thermodynamic Significance of Specific Impulse

1. Fundamental Thermodynamic Concepts

Thermodynamics is the science which deals with the relationships between various forms of energy. Applied to chemical reactions, thermodynamics not only reveals whether or not a reaction is possible but also specifies the quantitative change in energy which occurs during the reaction. Thermodynamics is independent of the path of a chemical reaction; only the initial and final states need be considered. However, thermodynamics has its limitations. Since it is not concerned with time, thermodynamics will yield no information concerning the rate and mechanism of a reaction.

The first law of thermodynamics is the law of conservation of energy. This states that the total energy entering a process, plus any addition during the process, must equal the total energy of the system leaving the process, i.e.

$$dE = dq - dw \quad (10)$$

where

E = internal energy of the system
 q = energy absorbed by the system from
its surroundings
 w = work done by the system on the
surroundings

The second law of thermodynamics may be considered as a measure of the degree to which energy can be transformed into useful work. The point property which measures the amount by which the energy of a system is degraded in going from one state to another is called entropy, and is defined by the second law as

$$dS = \frac{dq_r}{T} \quad (11)$$

where

S = entropy of the system
 T = temperature of the system
 q_r = reversible energy change at
 constant temperature

Interpreted statistically, the second law states that, on the average, the entropy of an isolated system increases continuously until that system reaches a state of maximum probability. In reality, all spontaneous reactions are to some extent irreversible and are accompanied by a degradation of energy. Finally, the third law of thermodynamics states that the absolute entropy of any homogeneous substance which is in complete internal equilibrium is zero at 0°K. The first two laws are explicitly involved in the analysis of rocket propulsion, while the third law is utilized implicitly.

Utilizing the first law, enthalpy is defined as

$$dH = dE + d(pV) \quad (12)$$

where

H = enthalpy
 E = internal energy
 p = pressure
 V = volume

Since enthalpy is defined in terms of functions of state, it is also a function of the state of a system. By re-writing the first law in the form

$$dq = \left(\frac{\partial E}{\partial T} \right)_V dT + \left[\left(\frac{\partial E}{\partial V} \right)_T + P \right] dV \quad (13)$$

the specific heat capacities are defined as

$$C_V = \left(\frac{\partial E}{\partial T} \right)_V \quad (14)$$

$$c_p = \left[\frac{\partial(E+pV)}{\partial T} \right]_p = \left(\frac{\partial H}{\partial T} \right)_p \quad (15)$$

for constant volume and constant pressure, respectively. For the general case,

$$c_p - c_v = \left[p + \frac{\partial E}{\partial V} \right]_T \left(\frac{\partial V}{\partial T} \right)_p \quad (16)$$

but for ideal gases this relationship reduces to $c_p - c_v = R$. (17)

In order to express the first and second laws explicitly in terms of temperature and pressure, the Gibb's free energy is defined as

$$dF = dH - d(TS) \quad (18)$$

$$\text{or} \quad dF = dE + pdV + Vdp - TdS - SdT \quad (19)$$

Under reversible conditions in which all work is accomplished by expansion,

$$dE = TdS - pdV. \quad (20)$$

Combining these equations,

$$dF = Vdp - SdT. \quad (21)$$

This is probably the most useful combined statement of the first and second laws since pressure and temperature are the independent variables. The concept of free energy is extremely useful as a criterion of chemical equilibrium, and is related to the equilibrium constant by the equation

$$dF = RT d \ln K. \quad (22)$$

At equilibrium, the free energy change of a chemical reaction is zero.

2. Application of Thermodynamics to Rocket Propulsion

All of these general thermodynamic relationships are employed in the analysis of the combustion and expansion processes of rocket propulsion. However, the particular thermodynamic significance of specific impulse is derived from the law of conservation of energy. For the macroscopic, steady-state flow process, Bernoulli's general energy equation per unit of mass becomes

$$\left[E_2 + Z_2 + \frac{v_2^2}{2g} + p_2 v_2 \right] - \left[E_1 + Z_1 + \frac{v_1^2}{2g} + p_1 v_1 \right] = q - W_o \quad (23)$$

where

E = internal energy of the fluid
 Z = potential energy of position
 v = fluid velocity
 pV = work of expansion
 q = energy absorbed by the system
from the surroundings
 W_o = non-expansion work done by the system

Position 1 represents the nozzle exhaust conditions while position 2 represents the combustion chamber conditions. Since the velocity is zero at stagnation conditions, v_2 drops from the equation. Also, the difference in potential energy between the chamber and the nozzle exit is negligible. Thus, the equation reduces to

$$\Delta E + \Delta(pV) - \frac{v_1^2}{2g} = q - W_o \quad (24)$$

or

$$\Delta H - \frac{v_1^2}{2g} = q - W_o \quad (25)$$

For an adiabatic process in which all work is accomplished by expansion,

$$\Delta H = \frac{v_1^2}{2g} \quad (26)$$

or

$$v_1 = \sqrt{2g \Delta H} \quad (27)$$

For the case of optimum expansion,

$$I_{sp} = \frac{v_e}{g} = \sqrt{\frac{2J}{g} \Delta H} \quad (28)$$

where

I_{sp} = specific impulse
 v_e = exhaust velocity
 g = acceleration of gravity
 J = mechanical equivalent of heat
 ΔH = enthalpy change

Thus, specific impulse may be defined rigorously from the total enthalpy change of the system between the combustion chamber and the nozzle exit. Numerically evaluating the specific impulse equation in English units,

$$I_{sp} = 6.940 \sqrt{H_c - H_e} \quad (29)$$

where

H_c = enthalpy of chamber gases, Btu/lb
 H_e = enthalpy of exhaust gases, Btu/lb
 I_{sp} = lb thrust/lb mass/second
 J = 778 ft-lb/Btu
 g = 32.2 ft/sec²

Similarly, evaluating the equation in metric units,

$$I_{sp} = 9.330 \sqrt{H_c - H_e} \quad (30)$$

where

H_c = enthalpy of chamber gases,
calories/gram
 H_e = enthalpy of exhaust gases,
calories/gram
 I_{sp} = lb thrust/lb mass/second

These equations are rigorous and apply to isentropic two-phase flow as well as to isentropic compressible flow. In the latter case, another form of the specific impulse equation may be utilized. Since $\left(\frac{\partial H}{\partial P}\right)_T = 0$ for an ideal gas, the adiabatic change in enthalpy is

$$H = \int c_p dt \quad (31)$$

Since
$$c_p = \frac{k}{k-1} R \quad (32)$$

$$\Delta H = \frac{k}{k-1} \cdot \frac{R}{MW} (T_o - T_e). \quad (33)$$

Under isentropic conditions,

$$T_e = T_o \left[\frac{P_e}{P_o} \right]^{\frac{k-1}{k}} \quad (34)$$

and
$$\Delta H = \frac{k}{k-1} \cdot \frac{RT_o}{MW} \left[1 - \left(\frac{P_e}{P_o} \right)^{\frac{k-1}{k}} \right] \quad (35)$$

Therefore,
$$v_e = \sqrt{\frac{2g R k}{k-1} \cdot \frac{T_o}{MW} \left[1 - \left(\frac{P_e}{P_o} \right)^{\frac{k-1}{k}} \right]} \quad (36)$$

from which
$$I_{sp} = \sqrt{\frac{2R}{g} \cdot \frac{k}{k-1} \cdot \frac{T_o}{MW} \left[1 - \left(\frac{P_e}{P_o} \right)^{\frac{k-1}{k}} \right]} \quad (37)$$

where

- T_o = combustion or stagnation temperature
- MW = mean molecular weight of combustion products
- k = mean ratio of the specific heat capacities of the exhaust gas, c_p/c_v
- P_o = chamber or stagnation pressure
- P_e = exhaust pressure
- I_{sp} = specific impulse
- R = gas constant
- g = acceleration of gravity

When $R = 1544 \text{ ft-lb/(mole)}(^{\circ}\text{R})$, $g = 32.2 \text{ ft/sec}^2$, and $T_0 = ^{\circ}\text{R}$,

$$I_{sp} = 9.797 \sqrt{\frac{k}{k-1} \cdot \frac{T_0}{MW} \left[1 - \left(\frac{p_e}{p_0} \right)^{\frac{k-1}{k}} \right]} \quad (38)$$

D. Steady, One-Dimensional, Isentropic, Compressible Flow

1. General Principles

An isentropic process is both reversible and adiabatic and may be considered as the limit to be approached by real adiabatic processes. As was discussed earlier, this approximation constitutes a limiting condition for expansion through a converging-diverging rocket nozzle. Compressible flow implies variations in density throughout the field of flow, resulting primarily from changes in pressure. The rate of change of density with respect to pressure is an important variable in the analysis of compressible flow and is inherently related to the velocity of propagation of a pressure disturbance.¹⁰ The one-dimensional flow approximation implies that the rate of change of fluid properties normal to the streamline is negligible compared to the rate of change along the streamline. If condensed phases are present during the expansion process, the concept of compressibility discussed in this section must be modified. Nevertheless, the principles which follow constitute a basic, useful approach to the analysis of rocket propulsion.

2. Velocity of Pressure Wave Propagation

For compressible flow, the Navier - Stokes' solution to the general equations of change may be written as¹¹

$$\frac{D\mathbf{v}_0}{Dt} = - (\nabla p) + \mu \left[\nabla \cdot (\nabla \mathbf{v}_0) \right] + \frac{1}{3} \left[\nabla (\nabla \cdot \mathbf{v}_0) \underline{\underline{v}} \right] + \sum F_i \quad (39)$$

In the absence of external and viscous forces, the Navier-Stokes' solution reduces to

$$\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} = - \frac{1}{\rho} \cdot \frac{\partial p}{\partial x} = - \frac{1}{\rho} \cdot \frac{\partial p}{\partial \rho} \cdot \frac{\partial \rho}{\partial x} \quad (40)$$

for one-dimensional flow. Similarly, the general equation of continuity for the fluid as a whole is

$$\frac{D\rho}{Dt} = - \rho (\nabla \cdot \mathbf{v}_0) \quad (41)$$

which reduces to

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v_x}{\partial x} + v_x \frac{\partial \rho}{\partial x} = \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho v_x) = 0 \quad (42)$$

for one-dimensional flow. Under steady-state conditions, these equations become¹²

$$v_x \frac{\partial v_x}{\partial x} = - \frac{1}{\rho} \cdot \frac{\partial p}{\partial \rho} \cdot \frac{\partial \rho}{\partial x} \quad (43)$$

and

$$\rho \frac{\partial v_x}{\partial x} = - v_x \frac{\partial \rho}{\partial x} \quad (44)$$

Simultaneous solution of the above equations defines the velocity of propagation of a pressure disturbance, or the velocity of sound, for one-dimensional, steady-state, ideal flow. As a limit, this velocity of propagation may be considered as isentropic for an infinitesimal

pressure disturbance, and expressed mathematically as

$$v_x = c = \sqrt{(\partial p / \partial \rho)_s} \quad (45)$$

For the isentropic flow of a perfect gas, $p/\rho = RT$ and p/ρ^k is a constant. Therefore,

$$\frac{dp}{p} = k \frac{d\rho}{\rho} \quad (46)$$

and

$$\left(\frac{\partial p}{\partial \rho}\right)_s = k \frac{p}{\rho} = kRT. \quad (47)$$

The velocity of sound may now be expressed as

$$c = \sqrt{\frac{kp}{\rho}} = \sqrt{kRT} \quad (48)$$

where

p = pressure
 ρ = density
 k = mean specific heat capacity ratio, c_p/c_v
 R = universal gas constant
 T = absolute temperature
 c = velocity of sound

3. Basic Flow Equations

Velocity, temperature, pressure, and density are the four independent properties selected to describe the state of the system.

Therefore, four independent equations are required to express the relationship between these properties at any two points in the nozzle.

These equations are: (1) the equation of conservation of mass; (2) the equation of conservation of momentum; (3) the equation of conservation of energy; and (4) the equation of state.

Under steady-state conditions, the mass rate of flow through a differential length of nozzle is

$$\Delta \rho \frac{\partial x}{\partial t} = \Delta \rho v \quad (49)$$

where

A = cross-sectional area
 ρ = fluid density
 v = fluid velocity
 x = distance along nozzle axis
 t = time

Therefore, the equation of conservation of mass is

$$\frac{d}{dx} (\Delta \rho v) = 0 \quad (50)$$

which, upon integration, becomes

$$\frac{m}{A} = \rho v \quad (51)$$

or

$$m = \frac{\Delta v}{V'} \quad (52)$$

where

m = mass rate of flow
 V' = specific volume of fluid

The rate of change of momentum at a particular inlet position is

$$\Delta \rho v \frac{\partial x}{\partial t} = \Delta \rho v^2 \quad (53)$$

while the rate of change of momentum at any downstream point is

$$\Delta \rho v^2 + \frac{d}{dx} (\Delta \rho v^2) dx \quad (54)$$

From Newton's laws of motion, the difference in these rates of change of momentum equals the resultant of the forces acting on the inclosed volume of fluid. These forces are an upstream force Δp on the inlet section, a downstream force $\Delta p + \frac{d}{dx} (\Delta p) dx$ on the exit section, and a

force $P_p \alpha dx$ exerted by the walls of the nozzle. In this latter case, P is the perimeter of the section and α is the half-angle of divergence of the nozzle. Thus,

$$-\frac{d}{dx} (A_p) dx + P_p \alpha dx = \frac{d}{dx} (A \rho v^2) dx \quad (55)$$

However, $dA = P dx \tan \alpha$ or $dA = P \alpha dx$ since α is small. Therefore, the equation of conservation of momentum may be written

$$-\frac{d}{dx} (A_p) + P \frac{dA}{dx} = \frac{d}{dx} (A \rho v^2) \quad (56)$$

or
$$A \frac{dp}{dx} + \frac{d}{dx} (A \rho v^2) = 0 \quad (57)$$

The total energy contained by the fluid stream consists of its internal energy and its kinetic energy. Using the previously developed nomenclature, the rate in influx of energy is

$$A \rho v \left(E + \frac{1}{2} v^2 \right) \quad (58)$$

while the rate of afflux of energy at a downstream position is

$$A \rho v \left(E + \frac{1}{2} v^2 \right) + \frac{d}{dx} \left[A \rho v \left(E + \frac{1}{2} v^2 \right) \right] dx \quad (59)$$

However, external forces are doing work on the gas at a rate $A p v$ on the inlet surface and at a rate $A p v + \frac{d}{dx} (A p v) dx$ on the outlet surface. Therefore, the total energy balance through the nozzle becomes

$$-\frac{d}{dx} (A p v) dx = \frac{d}{dx} \left[A \rho v \left(E + \frac{1}{2} v^2 \right) \right] dx \quad (60)$$

or
$$\frac{d}{dx} \left[A \rho v \left(E + \frac{p}{\rho} + \frac{1}{2} v^2 \right) \right] = 0. \quad (61)$$

In terms of enthalpy, the equation of conservation of energy is

$$\frac{d}{dx} \left[A \rho v \left(H + \frac{1}{2} v^2 \right) \right] = 0. \quad (62)$$

The equation-of-state for an ideal gas is $p/\rho = RT$. Since $dE = c_v dT$ and $c_p - c_v = R$,

$$d \left(\frac{p}{\rho} \right) = (c_p - c_v) \frac{dE}{c_v} \quad (63)$$

or

$$dE = \frac{1}{k-1} d \left(\frac{p}{\rho} \right) \quad (64)$$

Upon integration,

$$E = \frac{1}{k-1} \cdot \frac{p}{\rho} \quad (65)$$

4. Significance of the Mach Number

The equation of conservation of mass, the equation of conservation of momentum, and the Mach number are each independent of either the adiabatic or the isentropic restriction. This latter term, the Mach number, is a dimensionless quantity obtained from inspection analysis of the Navier-Stokes equations, and is defined as the ratio of stream velocity to the local velocity of sound, i.e.

$$M = \frac{V}{c} \quad (66)$$

The Mach number has a profound influence upon the nature of compressible flow, as shown by the following rigorous mathematical derivation.

By combining the continuity equation and the law of conservation of energy, the Bernoulli equation is obtained in differential form as

$$dH = -d\left(\frac{v^2}{2}\right) = -v dv \quad (67)$$

From thermodynamics,

$$Tds = dH - \frac{dp}{\rho} \quad (68)$$

which, at constant entropy, reduces to

$$dH = \frac{dp}{\rho} \quad (69)$$

Thus,

$$dp = -\rho v dv \quad (70)$$

This is Euler's equation of motion for an inviscid fluid, showing that pressure decreases with acceleration of flow and increases with deceleration of flow. Expressing the equation of continuity in logarithmic differential form,

$$d \ln p + d \ln A + d \ln v = 0 \quad (71)$$

$$\text{or} \quad \frac{dp}{p} + \frac{dA}{A} + \frac{dv}{v} = 0. \quad (72)$$

Substituting and rearranging,

$$\frac{dA}{A} = \frac{dp}{p} \left[\frac{1}{v^2} - \frac{\rho}{dp} \right] \quad (73)$$

$$\text{or} \quad \frac{dA}{A} = \frac{dp}{\rho v^2} \left[1 - \frac{v^2}{c^2} \right] = \frac{1-M^2}{\rho v^2} dp. \quad (74)$$

Thus, the following conclusions are reached:¹³

(1) For subsonic flow ($M < 1$),

$$\frac{dA}{dp} > 0 \quad \frac{dA}{dv} < 0 \quad (75)$$

(2) For sonic flow ($M = 1$),

$$\frac{dA}{dp} = 0 \quad \frac{dA}{dv} = 0 \quad (76)$$

(3) For supersonic flow ($M > 1$),

$$\frac{dA}{dp} < 0 \quad \frac{dA}{dv} > 0. \quad (77)$$

From these relationships, it is seen that the effect of an area change is exactly the opposite for subsonic and supersonic flow. This leads to the interesting conclusion that an accelerating stream starting from rest must first decrease in cross-sectional area until a velocity of Mach = 1 is attained. Then, the same stream must increase in cross-sectional area in order to reach supersonic velocities. In practice, this phenomenon is achieved with the converging-diverging nozzle.

5. Adiabatic Flow Relations

Since all possible states of isentropic flow lie on a line of constant entropy, one of these states must correspond to zero velocity. The conditions at this point, referred to as the stagnation conditions, are independent of any changes which may occur downstream. The stagnation enthalpy, temperature, and pressure are designated H_0 , T_0 , and p_0 respectively. Although the expansion process through the nozzle is isentropic, several useful flow restrictions are dependent only upon the adiabatic restriction. From the first law of thermodynamics, the total energy between the stagnation point and any downstream position must be conserved, i.e.

$$H_0 = H + \frac{v^2}{2g} \quad (78)$$

Also, under ideal conditions,

$$\Delta H = c_p \Delta T \quad (79)$$

$$c_p - c_v = R \quad (80)$$

$$c_p/c_v = k \quad (81)$$

$$c_p = \frac{k}{k-1} R \quad (82)$$

Thus, the velocity at any position may be expressed in terms of the stagnation temperature as

$$v = \sqrt{2 c_p (T_o - T)} = \sqrt{\frac{2k}{k-1} R (T_o - T)} \quad (83)$$

The ratio of the stagnation temperature to any adiabatic downstream temperature may be expressed in terms of Mach number and specific heat ratio. Again by the first law of thermodynamics,

$$\frac{T_o}{T} = 1 + \frac{v^2}{2c_p T} = 1 + \frac{v^2}{kRT} \cdot \frac{kR}{2c_p} \quad (84)$$

However, $c_p = \frac{k}{k-1} R$ and $c^2 = kRT$

Therefore,
$$\frac{T_o}{T} = 1 + \frac{k-1}{2} \cdot \frac{v^2}{c^2} \quad (85)$$

or
$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2 \quad (86)$$

Finally, the flow per unit area for any adiabatic process may be expressed as

$$\frac{\dot{m}}{A} = \rho v = \frac{p}{RT} v = \frac{pv}{\sqrt{kRT}} \sqrt{\frac{k}{R} \cdot \frac{T_o}{T} \cdot \frac{1}{T_o}} \quad (87)$$

$$\text{or} \quad \frac{\dot{m}}{A} = \sqrt{\frac{k}{R}} \cdot \frac{p}{\sqrt{T_0}} \cdot M \sqrt{1 + \frac{k-1}{2} M^2} \quad (88)$$

6. Isentropic Flow Relations

Under the conditions of isentropic flow, the pressure-volume-temperature relationship for ideal gases becomes

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} = \left(\frac{V_1}{V_2} \right)^{k-1} \quad (89)$$

Utilizing this, the pressure and density at any downstream position may be evaluated from the equations

$$\frac{p_0}{p} = \left[1 + \frac{k-1}{2} M^2 \right]^{\frac{k}{k-1}} \quad (90)$$

$$\text{and} \quad \frac{\rho_0}{\rho} = \left[1 + \frac{k-1}{2} M^2 \right]^{\frac{1}{k-1}} \quad (91)$$

Furthermore, the flow per unit area of cross-section now becomes

$$\frac{\dot{m}}{A} = \sqrt{\frac{k}{R}} \cdot \frac{p_0}{\sqrt{T_0}} \cdot \frac{M}{\left[1 + \frac{k-1}{2} M^2 \right]^{\frac{k+1}{2(k-1)}}} \quad (92)$$

By differentiating this equation with respect to M and setting the derivative equal to zero, it is found that the maximum \dot{m}/A exists at the throat where $M=1$.¹⁴ Thus, the maximum flow per unit area of cross-section is

$$\left(\frac{\dot{m}}{A} \right)_{\max} = \frac{\dot{m}}{A^*} = \sqrt{\frac{p_0}{T_0}} \sqrt{\frac{k}{R} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \quad (93)$$

where A^* denotes the throat area, or critical area, at $M = 1$. An area ratio between the throat and any downstream position may now be expressed as

$$\frac{A}{A^*} = \frac{m/A^*}{m/A} = \frac{1}{m} \left[\left(\frac{2}{k+1} \right) \left(1 + \frac{k-1}{2} M^2 \right) \right]^{\frac{k+1}{2(k-1)}} \quad (94)$$

For each equation containing the term M^2 , there is both a subsonic solution and a supersonic solution. It has been shown that the subsonic solution applies to the converging portion of the nozzle while the supersonic solution is valid in the diverging portion. Corresponding to any given value of Mach number, there is one precise value of p/p_0 , T/T_0 , ρ/ρ_0 , and A/A^* which can be evaluated from equations already discussed. Shapiro has tabulated a set of working tables in which these dimensionless ratios are summarized for an ideal gas having $k = 1.4$.

7. Choking and Nozzle Expansion

The fact that the mass flow rate per unit area possesses a maximum value at the throat leads to a phenomenon called choking. For a given converging-diverging nozzle operation under fixed stagnation conditions, the nature of the flow depends upon the pressure ratio p_e/p_0 . If the external downstream pressure is gradually reduced from an initial condition of $p_e = p_0$, the velocity through the converging section of the nozzle increases until $M = 1$ at the throat. This is the critical pressure ratio. Further reduction in the external pressure will result in supersonic flow being maintained beyond the throat. However, true isentropic flow beyond the throat can exist only if the external

pressure is equal to or less than the one specific ideal exhaust pressure defined by the nozzle area ratio. If the external pressure exceeds the ideal exhaust pressure but is less than the critical throat pressure, irreversible discontinuities occur in the diverging section of the nozzle. Although these discontinuities, called normal shock waves, may occur adiabatically, the entropy of the fluid is always increased. The normal discontinuity always involves a change from supersonic flow to subsonic flow accompanied by a pressure rise and an energy loss. The magnitude of this energy loss may be evaluated from the Fanno and Rayleigh curves for the particular expansion process. The Fanno line is the locus of points which satisfies the energy equation, continuity equation, and the equation of state. On the other hand, the Rayleigh line is the locus of points satisfying the momentum equation, the continuity equation, and the equation of state. A straight line connecting the two points of intersection of these loci represents the normal shock wave. Shapiro has also developed a set of working tables which relate the pressure ratio, density ratio, temperature ratio, and area ratio across the shock wave to the upstream and downstream Mach numbers.¹⁵

If the nozzle exit pressure exceeds the external pressure, the fluid will continue to expand after being exhausted from the nozzle. However, no useful work is derived from this free expansion. Three-dimensional turbulence occurs in the immediate region outside the nozzle. Again a loss of energy is incurred. Thus, either overexpansion or underexpansion of the working fluid results in reduced performance. Ideally, the nozzle exhaust pressure should equal the external downstream pressure.

8. Isentropic Flow Performance Parameters

By introducing the isentropic flow relationships into the velocity equations already developed, the exhaust velocity is evaluated as

$$v_e = \sqrt{\frac{2k}{k-1} R^0 \cdot g \frac{T_0}{MW} \left[1 - \left(\frac{p_e}{p_0} \right)^{\frac{k-1}{k}} \right]} \quad (95)$$

where

MW = molecular weight

R^0 = gas constant expressed in work units

The maximum possible exhaust velocity is obtained at an infinite pressure ratio p_0/p_e , for which the ideal cycle efficiency

$$\eta = 1 - \left(\frac{p_e}{p_0} \right)^{\frac{k-1}{k}}$$

becomes unity. When p_0/p_e becomes infinite,

$$v_{\max} = \sqrt{2g \cdot R \frac{k}{k-1} \cdot \frac{T_0}{MW}} \quad (96)$$

Simultaneously, T/T_0 and ρ/ρ_0 become zero while A/A^* becomes infinite.

This leads to the interesting conclusion that the maximum attainable exhaust velocity is finite even though the working fluid is expanded to an infinitely low pressure, temperature, and density. Earlier, the exhaust velocity was shown to be related to specific impulse by the equation

$$v_e = I_{sp} \cdot g$$

for ideal expansion.

Although the characteristic velocity c^* is readily evaluated from experimental data, its theoretical evaluation requires a knowledge of throat conditions. By combining the definition of c^* and the equation of continuity, the theoretical relationship becomes

$$c^* = \frac{p_c}{\rho^* v^*} \quad (97)$$

The conditions at the throat can be expressed in terms of the stagnation conditions as

$$\frac{p^*}{p_0} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \quad (98)$$

$$\frac{T^*}{T_0} = \frac{2}{k+1} = \left(\frac{c^*}{c_0} \right)^2 \quad (99)$$

$$\frac{\rho^*}{\rho_0} = \left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \quad (100)$$

where k is the average specific heat ratio between stagnation and throat conditions. However, an accurate determination of c^* is difficult because of the change of k with chemical reaction. Probably the most rigorous approach is to maximize ρv by calculating this quantity at several assumed throat pressures.

Since
$$v^* = c^* = \left(\frac{\partial n}{\partial \rho} \right)_s^{1/2} \quad (101)$$

and
$$p^* \cdot MW^* = \rho^* \cdot RT^* \quad (102)$$

$$c^* = \frac{p_o}{p^*} \cdot \frac{RT^*}{k^*MW^*} = \frac{p_o}{p^*} \left(\frac{T^*}{T_o} \right)^{1/2} \left(\frac{RT_o}{k^*MW^*} \right)^{1/2} \quad (103)$$

$$c^* = \sqrt{\frac{RT_o}{k^*MW^*} \left[\frac{k+1}{2} \right] \frac{k+1}{k-1}} \quad (104)$$

For the case of a non-reacting gas with constant specific heat, this equation is readily evaluated. Otherwise, a trial-and-error solution is required. In general, c^* may be considered as being affected by conditions upstream of the throat but as being independent of downstream conditions.

Theoretical evaluation of the thrust coefficient is also somewhat involved although its experimental evaluation is straightforward:

$$c_F = \frac{\frac{1}{2} \rho_e (1 + \cos \alpha) v_e + (p_e - p_a) A_e}{p_o A^*} \quad (105)$$

$$\text{or} \quad c_F = \frac{v_e}{c^*} + \frac{p_e - p_a}{p_o} \cdot \frac{A_e}{A^*} \quad (106)$$

Unlike c^* , c_F is a function of exit pressure and of nozzle geometry downstream of the throat. For ideal expansion, i.e. when $p_e = p_a$,

$$c_F = \frac{v_e}{c^*} \quad (107)$$

Expressing this relationship in terms of the flow equations for a chemically-reacting gas with variable specific heat,

$$c_F = \sqrt{\frac{2k^*}{k-1} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}} \left[1 - \left(\frac{p_e}{p_o} \right)^{\frac{k-1}{k}} \right]} \quad (108)$$

where

- \bar{k} = average specific heat ratio during expansion
- k = average specific heat ratio between the chamber and the throat
- k^* = average specific heat ratio at the throat

The thrust imparted to a missile may be expressed in terms of the thrust coefficient as

$$F' = A^* p_o c_F + (p_e - p_a) A_e \quad (109)$$

This applies either theoretically or experimentally. Finally, the area ratio may be expressed in terms of the pressure ratio and the specific heat ratio as

$$\frac{A}{A^*} = \frac{\left(\frac{p_o}{p}\right)^{\frac{1}{k}}}{\left(\frac{k+1}{2}\right)^{\frac{1}{k-1}} \sqrt{\frac{k+1}{k-1} \left[1 - \left(\frac{p}{p_o}\right)^{\frac{k-1}{k}}\right]}} \quad (110)$$

or in terms of the thrust coefficient as

$$\frac{A}{A^*} = \frac{k}{c_F} \left[\frac{2}{k+1}\right]^{\frac{k+1}{k-1}} \left[\frac{p_o}{p}\right]^{\frac{1}{k}} \quad (111)$$

E. Steady, One-Dimensional, Isentropic, Multi-Phase Flow

1. General Principles

The previous analysis of isentropic, compressible flow is completely rigorous only if all the products of combustion are ideal gases.

Theoretical analysis of the expansion process becomes considerably more complicated if a condensed phase is present during all or part of the expansion. Either solids, liquids, or both may be present in the products of combustion, depending upon the composition of the propellant and the operating conditions.

In any flow system consisting of more than one phase, the general equations of change apply in each phase. Furthermore, the solutions to the equations of change in the individual phases must be matched at the interfaces. In view of the fact that the mechanisms of the various interphase transfers have not been completely defined, a general multi-phase transport solution to the general equations of change has not been obtained.¹⁶ The problems of two-phase momentum transfer alone are quite complex and not adaptable to a simple, rigorous analytical solution. The simultaneous occurrence of heat and mass transfer adds to the complexity of the problem. Therefore, discussion of multi-phase flow in a converging-diverging nozzle will be limited to a semi-quantitative treatment. Using this approach, the degree of attainment of thermal and momentum equilibrium between the gas phase and the condensed phases can be analyzed.

By applying the assumptions which were presented and discussed previously, thermodynamic relations can be formulated for: (1) the case of a condensed phase existing in constant concentration throughout

the expansion; and (2) the case of condensation during expansion. In the latter case, the concentration of the condensed phase is a function of the temperature, pressure, and rate of condensation. Whereas for isentropic flow of a perfect gas,

$$pV^k = \text{constant} \quad (112)$$

the corresponding relationship for isentropic, multiphase flow is¹⁷

$$pV^\phi = \text{constant} \quad (113)$$

$$\text{where} \quad \phi = \frac{a_1 R + a_1 c_{Vg} + Mwa_2 c_{ps}}{a_1 c_{Vg} + Mwa_2 c_{ps}} \quad (114)$$

- p = pressure
- V = volume
- c_{Vg} = constant volume specific heat capacity of the gas phase
- c_{ps} = constant pressure specific heat capacity of the condensed phase
- MW = mean molecular weight of the gas phase
- a_1 = mass fraction of gas phase
- a_2 = mass fraction of condensed phase
- k = c_{pg}/c_{Vg}
- R = gas constant ($c_{pg} - c_{Vg}$)

This latter equation includes the specific heat capacity of the condensed phase while retaining the form of the equation for the isentropic flow of gases. Evaluating the relationship between k and ϕ ,

when $a_2 = 0$, $\phi = \frac{R+c_{vg}}{c_{vg}} = k$

when $a_2 > 0$, $k > \phi > 1$

2. Flow with Constant Concentration of Condensables

For the case in which a condensed phase exists in constant concentration during the expansion process, the enthalpy balance for adiabatic, frictionless flow is¹⁸

$$dH = c_{pg} dT_g + f c_{ps} dT_s = V'_g dp = \bar{R} T_g \frac{dp}{p} \quad (115)$$

where

- H = enthalpy of multiphase system
- c_{pg} = specific heat of gas per unit mass
- c_{ps} = specific heat of condensed phase per unit mass
- f = mass ratio of solid to gas
- T_g = temperature of gas
- T_s = temperature of condensed phase
- p = pressure
- V'_g = specific volume of gas
- \bar{R} = R/MW

Integrating,

$$H_c - H_e = c_{pg} (T_c - T_{eg}) + f c_{ps} (T_c - T_{es}) = \frac{1}{2} (v_g^2 + f v_s^2) \quad (116)$$

where

- c denotes chamber conditions
- e denotes exhaust conditions

The relationship between temperature, pressure, and heat capacity is

$$\left[c_{pg} + f c_{ps} \frac{dT_s}{dT_g} \right] \frac{dT_g}{T_g} = \bar{R} \frac{dp}{p} \quad (117)$$

Assuming that $\frac{dT_s}{dT_g}$ varies linearly with pressure, the integrated form of the above equation becomes

$$\frac{T_{e_g}}{T_c} = \left[\frac{p_e}{p_c} \right]^{\frac{\bar{R}}{c_{p_g} + f c_{p_s}} \frac{dT_s}{dT_g}} \quad (118)$$

For the limiting condition of $T_s = T_g = T$,

$$\frac{T_e}{T_c} = \left[\frac{p_e}{p_c} \right]^{\frac{\bar{R}}{c_{p_g} + f c_{p_s}}} \quad (119)$$

while for the other extreme of $T_s = T_c$, $dT_s = 0$

and

$$\frac{T_e}{T_c} = \left[\frac{p_e}{p_c} \right]^{\frac{\bar{R}}{c_{p_g}}} \quad (120)$$

For the general case,

$$\left[c_{p_g} + f c_{p_s} \frac{dT_s}{dT_g} \right] (T_c - T_{e_g}) = \frac{1}{2} v_g^2 \left[1 + f \frac{v_s^2}{v_g^2} \right] \quad (121)$$

3. Flow with Simultaneous Condensation

If condensation occurs during the expansion, the flow conditions are altered considerably since the phase change from gas to liquid or solid is accompanied by the release of heat and a decrease in the quantity of working fluid. Assuming thermal and kinetic equilibrium for the condensed phase, the enthalpy balance is¹⁹

$$dH = c_{p_g} dT + f c_p dT + \Delta H_v dn_g = V'_g dp \quad (122)$$

where

- ΔH_v = molar latent heat of phase change
- n_g = moles of gas
- c_p = specific heat capacity of the newly formed condensed phase (solid or liquid)

By applying the ideal gas law,

$$\left[c_{pg} + f c_{pe} + \Delta H_v \left(\frac{dn_g}{dT} \right) \frac{dT}{dt} \right] \frac{dT}{T} = n_g R \frac{dp}{p} = \bar{R} \frac{dp}{p} \quad (123)$$

This equation can be solved only if $\frac{dn_g}{dt}$, the rate of condensation or nucleation, is known as a function of temperature and pressure. Although a considerable amount of work has been done on the rates of nucleation, the equations are too complex to be readily solved. Qualitatively, the theory shows that the rate of condensation increases with the ratio of the actual vapor pressure to the saturation vapor pressure.²⁶ During a flow process, the rate of condensation will always lag somewhat behind that value required to maintain equilibrium.

4. Approach to Momentum Equilibrium

In order to evaluate the order of magnitude of momentum and heat transfer between the gas and condensed phases, the semi-quantitative treatment will be extended to these phenomena. The condensed particles will be assumed to be spherical. Using this approximation, the force or drag acting on a moving spherical body is

$$F_p = m'a' = \frac{1}{2} C_D A' \rho_g (v_g - v_s)^2 \quad (125)$$

where

F_p = force acting on the particle

m' = mass of particle

a' = acceleration of particle

C_D = drag coefficient

ρ_g = density of gas

A' = frontal area of body = πr^2

v_g = velocity of gas phase

v_s = velocity of condensed particle

The mass of the particle is

$$m' = \frac{4}{3} \pi \rho_s r^3 \quad (126)$$

from which the acceleration of the particle is

$$a' = \frac{dv_s}{dt} = \frac{3\rho_g C_D}{8\rho_s r} (v_g - v_s)^2 \quad (127)$$

Although a rigorous solution of this equation requires the experimental evaluation of the drag coefficient, an approximate treatment may be based upon Stokes' Law. The equation of motion for spherical particles under the influence of Stokes' drag is

$$m' \frac{d^2x}{dt^2} = 6\pi\mu_g r (v_g - v_s) \quad (128)$$

where

m' = mass of particle
 μ_g = viscosity of the gas (assumed constant)
 r = radius of particle

This equation cannot be integrated directly for the general case, but an exact solution is obtained for linear acceleration of the gas stream, i.e.

$$v_g = (v_{g0} + 2a'x)^{\frac{1}{2}} \quad (129)$$

By combining these two equations and using the relationship $v_s = \frac{dx}{dt}$,

$$m \frac{d^2x}{dt^2} + 6\pi\mu_g r \frac{dx}{dt} - 6\pi\mu_g r (v_{g0}^2 + 2ax)^{\frac{1}{2}} = 0 \quad (130)$$

where

v_{g0} = gas velocity at the instant the particle under consideration is injected into the gas stream

A more useful expression of these relationships is

$$\frac{dv_s}{dx} = \frac{6\pi\eta r_g}{m'v_{g0}} \left[\frac{v_s}{v_g} - 1 \right] \quad (131)$$

and

$$\left(\frac{v_g}{v_{g0}} \right)^2 = 1 + \frac{2a'x}{v_{g0}^2} \quad (132)$$

where

$$\frac{v_g}{v_{g0}} = 1 \quad \text{and} \quad \frac{v_s}{v_{g0}} = 0 \quad \text{at} \quad x = 0.$$

In rapidly accelerating flow, the Reynold's number for the particle may readily exceed the limit for Stokes' drag. The equation of motion then takes the non-linear form²²

$$m' \frac{d^2x}{dt^2} = \frac{\pi}{2} C_D r^2 (v_g - v_s)^2 \quad (133)$$

However, provided the Stokes' drag coefficient is $c_d = 24/Re$, the acceleration is found to be

$$\frac{dv_s}{dt} = \frac{9\eta}{2r^2} (v_g - v_s) \quad (134)$$

This equation may be solved with the aid of the equation for the conservation of energy and the equation for the rate of temperature change dT/dt . Maxwell reports that when $r = 5 \times 10^{-5}$ cm, $v_s = 0.98 v_g$ after only 4% of the particle's residence time in the nozzle has elapsed.²³

5. Approach to Thermal Equilibrium

Analysis of thermal equilibrium between the gas and condensed phases is somewhat more complex because three major heat transfer mechanisms are involved. These are convective heat transfer between the particles and the gas, heat transfer within the particle, and radiation from the particle. The convective heat transfer from the

condensed particle to the gas may be represented by

$$\frac{dq'}{dt} = h A' (T_s - T_g) \quad (135)$$

where

h = average heat transfer coefficient
 A' = effective surface area
 q' = total heat transferred

Assuming instantaneous heat transfer within the particle,

$$\frac{dq'}{dt} = -c_{ps} \frac{dT_s}{dt} = hA'(T_s - T_g) \quad (136)$$

and for spherical particles

$$-\frac{dT_s}{dt} = \frac{3h}{\rho_s c_{ps} r} (T_s - T_g) \quad (137)$$

This shows that the rate of heat transfer increases as the particle size decreases. Altman and Carter report that $T_s - T_g$ will be less than 100°K provided r does not exceed 10^{-4} cm diameter.²⁴ Assuming that heat transfer is rapid at the surface of the particle, the limitation on the rate of transfer will be thermal conductivity within the particle. Altman and Carter have also shown that this is rapid for particles of less than 10^{-5} cm diameter. The borderline for adequate conduction appears to lie between diameters of 10^{-3} and 10^{-4} cm.

The energy emitted from the condensed particle by radiation is

$$-\frac{dE'}{dt} = 4\pi r^2 \epsilon \sigma T^4 \quad (138)$$

where

σ = Stefan-Boltzmann constant
 ϵ = emissivity constant
 E' = energy transferred by radiation

For spherical particles,

$$-\frac{dT}{dt} = \frac{3\epsilon T^4}{\rho_s c_{ps} r} \quad (139)$$

Altman and Carter report that very little energy is lost by radiation from particles which exceed 10^{-2} cm diameter. On the other hand, the rate of the temperature drop of particles less than 10^{-5} cm diameter can exceed that of the gas during expansion.²⁵ Maxwell reports that particles not exceeding 5×10^{-5} cm diameter can decrease in temperature as rapidly as the gas with a temperature difference of 20°K being maintained between phases.²⁶

From the previous discussion, it may be concluded that both momentum and thermal equilibrium between the gas phase and the condensed phase are rapidly approached provided the particle diameters are less than 10^{-4} cm. As the particle size increases, the degree of attainment of equilibrium decreases. The following table, prepared by Altman and Carter, shows a tabulation of specific impulse values for both complete thermal equilibrium and complete lack of thermal equilibrium at various assumed particle velocities corresponding to a mass fraction of 20% solid;²⁷

$\frac{v_s}{v_g}$	Isp at $T_s=T_g$	Isp at $T_s=T_c$
0	206	203
0.25	217	214
0.50	224	221
1.00	230	227

From a practical viewpoint, this table shows that the attainment of momentum equilibrium has more significance than the attainment of thermal equilibrium. Under Altman's assumed set of conditions, a maximum Isp change of 1 1/2% can result from non-thermal equilibrium while a maximum Isp change of almost 10% can result from non-momentum equilibrium.

6. Fundamental Equations of Flow

Assuming the validity of thermal and momentum equilibrium between the gas phase and condensed phase, there is no difference between the properties of the multiphase mixture and the ideal gas considered in the previous section on compressible flow. The general equations of conservation of mass, momentum, and energy remain valid. The equation of state is now expressed as

$$E = \frac{1}{\phi - 1} \cdot \frac{p}{\rho} \quad (140)$$

where ϕ has replaced k . Similarly, the isentropic flow relations and the isentropic performance parameters for compressible flow may be adapted to multiphase flow by replacing k by the modified specific heat ratio ϕ .

Since ϕ is less than k , the volume of the system becomes more sensitive to adiabatic pressure variations when condensed phases are present. This result applies only to adiabatic pressure changes when both compressibility and heat transfer are involved. As the concentration of the condensed phase is increased, the nozzle discharge coefficient increases. This is to be expected since the condensed

phase possesses a much greater density. Hence, the condensed phase is more readily transported through the nozzle throat where the rate of flow is limited by choking. The presence of a condensed phase has a relatively minor effect on the nozzle thrust coefficient. In fact, this is also as expected since the thrust coefficient is comparatively insensitive to variations in the adiabatic exponent k for pure gases. The presence of a condensed phase necessitates a somewhat larger nozzle area ratio in order to achieve optimum results. From a practical standpoint, phase separation is more likely to occur as the concentration of condensables is increased. Therefore, a smaller angle of divergence is desirable in the nozzle.

7. Uncertainties in Multi-Phase Flow

Earlier it was pointed out that the only fundamental uncertainties related to theoretical performance calculations are those concerned with the phenomenon of multi-phase flow. Additional fundamental studies are needed on the attainment of momentum equilibrium between phases, particularly when the condensed-phase content of the system is 80-90% by weight. Existing data are confined to the range of 20-35% by weight condensables. Conceivably, the energy losses due to drag could be more appreciable at the higher condensed particle loading. Also, upon expanding such systems to sub-atmospheric pressures, phase separation in the nozzle may be a more severe problem. Another fundamental uncertainty of potential significance involves the rate of formation and growth of condensed particles. This factor affects not only the size of the condensed particles but also the attainment of chemical and phase equilibrium during combustion and expansion. The questions of miscibility between condensed species, gas solubility in condensed phases, and non-ideality of condensable vapors are, in all probability of lesser consequence.

F. Ballistic Importance of Specific Impulse

From the previously developed equations, it has been shown that specific impulse rigorously defines the amount of useful energy which may be obtained from the combustion and expansion of a fuel and oxidizer. As an approximation, specific impulse is directly proportional to the square root of the combustion temperature divided by the mean molecular weight of the exhaust products. The effect of the specific heat ratio upon specific impulse is not as significant as the effect of the combustion temperature and the mean molecular weight of the exhaust products.

In addition to its thermodynamic significance, specific impulse also possesses an inherent ballistic importance. The burnout velocity, the vertical range, the horizontal range, the payload weight, and the physical size of a missile are all influenced by the specific impulse of the propellant. Tormey lists the general relationships between specific impulse and these various vehicle performance characteristics as,²⁸

$$(1) \text{ Burnout velocity} = I_{sp} \cdot g \cdot \ln \frac{W_i}{W_f} \quad (141)$$

$$(2) \text{ Vertical range} = h_{bo} + K' I_{sp} \ln \left[\frac{W_i}{W_f} \right]^2 \quad (142)$$

$$(3) \text{ Horizontal range} = 2S_{bo} + K' I_{sp} \ln \left[\frac{W_i}{W_f} \right]^2 \quad (143)$$

$$(4) \text{ Payload} = f(I_{sp})(W_o)(W_s) \quad (144)$$

$$(5) \text{ Physical size} = f(I_{sp})(\rho_{bulk}) \quad (145)$$

where

I_{sp}	=	specific impulse, seconds
W_i	=	total initial mass of the vehicle and its propellant
W_f	=	total final mass of vehicle after burnout
g	=	acceleration of gravity
h_{bo}	=	height of missile at burnout
S_{bo}	=	horizontal distance of the missile from its launching point at burnout
K'	=	physical constant
\ln	=	natural logarithm to the base e

These five equations are necessarily quite general and are presented to convey the concept rather than the quantitative relationship between specific impulse and the performance parameters. In practice, exact values for range, payload, size, and vertical height must be determined by a detailed analysis of the powerplant and the rocket vehicle. These values are dependent upon a series of arbitrary design choices, e.g. thrust-to-weight ratio, staging, trajectory, etc. Nevertheless, the preceding equations point out the overall importance of specific impulse in rocketry and that increases in specific impulse will lead to increases in missile performance.²⁹ The first equation of the series, which relates specific impulse to the burnout velocity of the missile, is examined in more detail in the next section.

G. Relationship between Specific Impulse and Propellant Density

1. Introduction

Specific impulse is the criterium generally used for comparing the relative capabilities of propellant combinations. However, in applying rocket propellants to a specific unit of hardware, the propellant density must also be considered in order to optimize performance.

Both of these parameters influence the incremental boost velocity imparted to a missile by the combustion of a propellant. The actual relationship between specific impulse and propellant density is a complicated one, particularly for multistage missiles, and depends upon the specific missile application. Such a detailed analysis is beyond both the theoretical and calculational scope of this report. However, a simplified theoretical discussion is presented to point out the roles of both parameters in the application of propellant systems to actual missiles.

2. The Mass-to-Volume Ratio Approach

The combined effect of specific impulse and density on the incremental boost velocity imparted to a missile is obtained by applying Newton's laws of motion to the missile:³⁰

$$W_m \frac{dv_b}{dt} = -I_{sp} \cdot g \frac{dW_m}{dt} + g \cdot A_e (P_e - P_a) - W_m \cdot g' \sin \beta - u^2 \gamma \quad (146)$$

where

- W_m = total mass of missile
- v_b = velocity of the missile
- t = time
- I_{sp} = propellant specific impulse
- g = acceleration of gravity (32,174 ft/sec²)
- g' = local acceleration of gravity
- A_e = nozzle exit area
- P_e = nozzle exhaust pressure
- P_a = external surrounding pressure
- β = angle of trajectory with the horizontal
- γ = empirical coefficient dependent upon physical conditions of the system and surroundings, e.g., missile surface area, density of surrounding medium, etc.

This generalized equation includes the effects of pressure thrust, gravity, and aerodynamic drag, in addition to momentum thrust. However, for the ideal case, only the momentum thrust must be considered. Then, the previous equation reduces to

$$W_m \frac{dv_b}{dt} = - I_{sp} \cdot g \cdot \frac{dW_m}{dt} \quad (147)$$

$$\text{Integrating, } v_b = I_{sp} \cdot g \cdot \ln \frac{W_m}{W_f} = I_{sp} \cdot g \cdot \ln \frac{W_m}{W_m - W_p} \quad (148)$$

where
 v_b = incremental increase in missile velocity
 W_m = total mass of missile (hardware and propellant)
 W_p = mass of propellant
 W_f = mass of missile hardware (payload and inert arts)

$$\text{or} \quad v_b = I_{sp} \cdot g \cdot \ln \left[1 + \frac{W_p}{W_f} \right] \quad (149)$$

$$\text{Since} \quad W_p = V_p \rho \quad (150)$$

$$v_b = I_{sp} \cdot g \cdot \ln \left[1 + \frac{V_p}{W_f} \right] \quad (151)$$

$$\text{or} \quad v_b = I_{sp} \cdot g \cdot \ln \left[1 + \frac{\rho}{W_f/V_p} \right] \quad (152)$$

where
 ρ = density of the propellant
 V_p = volume of propellant in missile
 W_f = mass of hardware

This equation enables the ideal boost velocity to be expressed in terms of the propellant density and specific impulse for a given mass-to-volume ratio, i.e. for a given mass of hardware per volume of propellant. This, of course, represents a simplified situation. In practice, a

change of propellant usually is accompanied by a change in hardware design. Nevertheless, the previous equation shows that the incremental boost velocity becomes independent of propellant density when the mass-to-volume ratio becomes zero. On the other hand, density becomes equally significant with specific impulse only at an infinite mass-to-volume ratio. Therefore, a change in specific impulse is always more significant than a corresponding change in propellant density on overall missile performance.

3. The Relative Effectiveness Approach

For the same situation in which various propellants are compared in a given unit of hardware, the relationship between specific impulse and density may also be evaluated by Geckler's approach.³¹ Neglecting the effect of aerodynamic drag and incremental changes in gravity,

$$v_b = I_{sp} \cdot g \ln \frac{W_m}{W_f} = I_{sp} \cdot g \ln \frac{W_m}{W_m - W_p} \quad (153)$$

where

- v_b = burnout velocity of missile
- I_{sp} = specific impulse of propellant
- g = acceleration of gravity
- W_m = total mass of missile
- W_p = mass of propellant
- W_f = final mass at burnout ($W_m - W_p$)

Differentiating,

$$dv_b = I_{sp} \cdot g \, d \left[\ln \frac{W_m}{W_f} \right] + \ln \frac{W_m}{W_f} \cdot d (I_{sp} \cdot g) \quad (154)$$

or

$$dv_b = I_{sp} \cdot g \cdot d \left[\frac{W_m}{W_f} \right] \cdot \frac{1}{W_m/W_f} + \ln \frac{W_m}{W_f} \cdot d (I_{sp} \cdot g) \quad (155)$$

Dividing by v_b , $\frac{dv_b}{v_b} = \frac{I_{sp} \cdot g}{v_b} \cdot d \left[\frac{w_m}{w_f} \right] \cdot \frac{1}{w_m/w_f} + \frac{\ln(w_m/w_f)}{v_b} \cdot d(I_{sp} \cdot g)$ (156)

and $\frac{dv_b}{v_b} = \frac{d(I_{sp} \cdot g)}{I_{sp} \cdot g} + \frac{I_{sp} \cdot g}{v_b} \cdot d \left[\frac{w_m}{w_f} \right] \cdot \frac{1}{w_m/w_f}$ (157)

For a constant volume of propellant, changes in mass arise only from a change in propellant density, so

$$dw_p = v_p d\rho \quad (158)$$

and $d \left[\frac{w_m}{w_f} \right] \cdot \frac{1}{w_m/w_f} = \frac{v_p d\rho}{w_m} = \frac{w_p}{w_m} \cdot \frac{d\rho}{\rho}$ (159)

Hence, $\frac{dv_b}{v_b} = \frac{d(I_{sp} \cdot g)}{I_{sp} \cdot g} + \frac{I_{sp} \cdot g}{v_b} \cdot \frac{w_p}{w_m} \cdot \frac{d\rho}{\rho}$ (160)

The term $\frac{I_{sp} \cdot g}{v_b} \cdot \frac{w_p}{w_m}$

must be unity in order for the density and specific impulse to be equally influential on burnout velocity. This term, which may be considered a "relative effectiveness coefficient", can be expressed as

$$\frac{\frac{w_p}{w_m}}{\ln \left[\frac{1}{1 - \frac{w_p}{w_m}} \right]}$$

where w_p/w_m is the propellant mass fraction. Upon numerical evaluation, the following relationship is found:³²

Propellant
Mass Fraction

Relative Effectiveness
of Density to Specific Impulse

0.95	0.317
0.90	0.391
0.85	0.448
0.80	0.497
0.75	0.541
0.70	0.581
0.60	0.656
0.50	0.721
0.40	0.783
0.30	0.839
0.20	0.896
0.10	0.958

For example, for a missile with a propellant mass fraction of 0.90, a change in density is 39.1% as significant as a corresponding percentage change in specific impulse.

4. The Arbitrary Parameter Approach

A third semi-rigorous approach has been presented by L.J. Gordon in which an arbitrary parameter is defined in terms of specific impulse and density as³³

$$b = I_{sp} \rho^s \quad (161)$$

where

I_{sp} = specific impulse
 ρ = density
 b = arbitrary parameter proportional to boost velocity
 s = empirical constant dependent upon missile design conditions

The parameter b is approximately proportional to the boost velocity for a propellant under the missile design conditions used for computing the exponent s , which is always contained within the limits $0 \leq s \leq 1$.

Also, the exponent s is assumed to be independent of density. In logarithmic form, the previous equation becomes

$$\log b = \log I_{sp} + s \log \rho \quad (162)$$

This is the slope-intercept form of the equation for a straight line and enables propellants to be compared graphically as a series of straight lines for a fixed design condition. The ordinate corresponding to $s = 0$ is the $\log I_{sp}$.

Previously, the ideal boost velocity was shown to be

$$v_b = I_{sp} \cdot g \ln \frac{W_0}{W_f} = I_{sp} \cdot g \ln \left[1 + \frac{\rho}{W_f/V_p} \right] \quad (163)$$

From this, the exponent s is defined as

$$s = \frac{\left(\frac{\partial v_b}{\partial \rho} \right)_{I_{sp}}}{\left(\frac{\partial v_b}{\partial I_{sp}} \right)_{\rho}} = \frac{\rho}{v_b} \left(\frac{\partial v_b}{\partial \rho} \right)_{I_{sp}} \quad (164)$$

For the simplified case of a constant ratio of hardware mass to propellant volume, the exponent s may be evaluated as

$$s = \frac{\frac{V_p}{W_f} \cdot \rho}{\left[1 + \frac{V_p}{W_f} \cdot \rho \right] \ln \left[1 + \frac{V_p}{W_f} \cdot \rho \right]} = \frac{B-1}{B \ln B} \quad (165)$$

where

$$B = 1 + \frac{V_p}{W_f} \cdot \rho \quad (166)$$

When $W_f/V_p = 0$, the exponent $s = 0$. When $W_f/V_p = \infty$, the exponent $s = 1$.

By evaluating s for various propellant densities, it can be shown that s possesses a relatively constant value at fixed design conditions.

Another fundamental design situation is that of constant hardware and propellant weight, with the volume of propellant being a variable. In this situation, rigorous evaluation of

$$s = \frac{\rho}{v_b} \left(\frac{\partial v_b}{\partial \rho} \right)_{Isp} \quad (167)$$

yields a cumbersome mathematical expression. However, by assuming differential increments of v_b and ρ over a small range, it can be shown that the exponent s is much less than for the previous case of constant missile volume. Both of these cases have considered single stage missiles only.

Calculations of single stage boost velocities based on constant volume of propellant ignore the fact that the stage weight varies with density. Neglecting structural features, thrust levels, and other variables which may have to be changed if a stage weight is changed, Gordon has also examined the effect of changing the propellant density in the second stage of a two-stage missile on the mass ratio of the first stage.³⁵ It is assumed that the two-stage missile has been designed to give equal boost velocity increments when both stages are loaded with the same propellant. However, this condition will not be maintained if different propellants are considered in each stage.

The total boost velocity may be expressed as

$$v_b = v_{b1} + v_{b2} = (Isp)_1 g \cdot \ln \left(\frac{W_m}{W_f} \right)_1 + (Isp)_2 g \cdot \ln \left(\frac{W_m}{W_f} \right)_2 \quad (168)$$

Applying the concept of $b = Isp \cdot \rho^s$, the exponent s must now be defined as

$$s = \frac{\frac{\rho}{v_b} \left(\frac{\partial v_b}{\partial \rho} \right)_{Isp}}{\frac{Isp}{v_b} \left(\frac{\partial v_b}{\partial Isp} \right)_{\rho}} = \frac{\rho}{Isp} \left(\frac{\partial v_b}{\partial \rho} \right)_{Isp} \left(\frac{\partial Isp}{\partial v_b} \right)_{\rho} = - \frac{\rho}{Isp} \left(\frac{\partial Isp}{\partial \rho} \right)_{v_b} \quad (169)$$

This implies that s is the rate at which a change in propellant density affects the boost velocity relative to the rate at which a change in specific impulse affects the boost velocity. A rigorous mathematical solution of the previous equation would be quite cumbersome. However, by assuming incremental numerical changes in specific impulse and density, Gordon has shown that the resultant value of s is about one-half that for a single stage vehicle at the same ratio of W_e/V_p .³⁶ Hence, the effect of propellant density on overall missile boost velocity is only about one-half as great in the second stage of a two-stage missile as in a single stage vehicle having the same fixed design criteria. This further emphasizes the relative importance of propellant specific impulse as the key parameter in overall missile performance.

CHAPTER IV

THERMODYNAMIC ANALYSIS OF PROPELLANT PERFORMANCE

In the previous discussion of the fundamental theory of rocket propulsion, specific impulse was shown to be measured by the change in enthalpy of the combustion products during an isentropic expansion through a converging-diverging nozzle. Also, the basic assumptions to be employed in performance calculations were presented and discussed as were the fundamentals of both compressible and multiphase nozzle flow. In this section, two rigorous methods of conducting performance calculations are presented. The basic thermodynamic properties of temperature, enthalpy, and entropy of the combustion products are calculated at the chamber and at the nozzle exit in each method. By using these properties and the chemical composition of the combustion products, other properties, such as the moles of gas, the specific heat capacity, the specific heat ratio, and the molecular weight of the products may be evaluated.

In the first method, thermodynamic equilibrium constants are utilized to express the concentration of certain chosen species in terms of the concentrations of other more abundant species. The solution is a trial-and-error one in which the chamber enthalpy balance and the nozzle entropy balance are conducted as assumed chamber and exit temperatures, respectively. The second method, which was utilized in the calculations presented later in this report, is a more general one and is applicable to all equilibrium reactions. Instead of utilizing arbitrary equilibrium constants, solution is obtained by minimizing the

total chemical potential, or free energy, of the complex mixture of combustion products. The combustion and exhaust temperatures are obtained as part of the solution so that these quantities do not enter into the trial-and-error iteration. The accuracy of both methods is dependent only upon the accuracy of the basic thermodynamic data for the reactants and the products of combustion. Sample performance calculations for both methods are included as Appendices.

A. Method of Thermodynamic Equilibrium Constants

1. General Approach

This method may be subdivided into the following steps, each of which will be presented and discussed in detail:

- (1) The propellant composition, the combustion pressure, and exhaust pressure are selected.
- (2) The products of combustion are qualitatively selected, and independent mass balance and chemical equilibria equations are written to allow simultaneous solution of the system.
- (3) At an assumed combustion temperature, the composition of the chamber products is calculated to a predetermined degree of accuracy.
- (4) An enthalpy balance is made at the assumed combustion temperature by comparing the enthalpy of the chamber products to the enthalpy of the propellant. Steps (3) and (4) are repeated until the combustion temperature is defined, i.e. the enthalpy balance is satisfied.
- (5) The entropy of the combustion products is calculated at the correct chamber temperature.
- (6) At an assumed exhaust temperature, the composition of the exhaust products is calculated to a predetermined degree of accuracy.

- (7) An entropy balance is made at the assumed exhaust temperature by comparing the entropy of the combustion products in the chamber and at the nozzle exit. Steps (6) and (7) are repeated until the exhaust temperature is defined, i.e. the entropy balance is satisfied.
- (8) The enthalpy of the exhaust products is calculated at the correct exhaust temperature.
- (9) The various other thermodynamic and rocket performance parameters are evaluated.

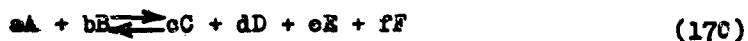
2. Selection of Operating Conditions

To determine the optimum performance of a given propellant system, detailed calculations must be made at several fuel-oxidizer ratios. In practice, the operating and exhaust pressures are dictated by the rocket hardware and the mission to be performed. However, since specific impulse is dependent upon the combustion and exhaust pressures, a standard basis of comparison must be chosen for theoretical calculations. By tradition most solid propellant performance calculations are reported at chamber pressures of 1000 PSIA expanded to 14.7 PSIA. On the other hand, liquid propellant performance calculations are frequently reported at chamber pressures of 300 PSIA, 500 PSIA, or 600 PSIA expanded to 14.7 PSIA. However, recently the desire has been expressed to standardize all performance calculations at chamber pressures of 1000 PSIA expanded to 14.7 PSIA. This practice has been followed in the calculations presented later in this report, particularly in view of their basic prototype nature.

3. Mass Balances and Chemical Equilibria

The composition of the combustion products is obtained by the simultaneous solution of independent equations expressing mass balances and chemical equilibria. The total number of equations to be solved must equal the number of individual species present in the combustion products. One mass balance may be written for each element present in the propellant. The remainder of the equations must come from equilibria relationships. Although the total moles of gaseous products is also a variable, this quantity may be obtained from the summation of the individual contributions of the various gaseous species.

For the general chemical reaction



the equilibrium constant may be expressed as

$$K_p = \frac{p_C^c \cdot p_D^d \cdot p_E^e \cdot p_F^f}{p_A^a \cdot p_B^b} \quad (171)$$

or

$$K_n = \frac{n_C^c \cdot n_D^d \cdot n_E^e \cdot n_F^f}{n_A^a \cdot n_B^b} \quad (172)$$

where

A, B, C, etc. = chemical reactants or products

a, b, c, etc. = number of moles or the respective components A, B, C, etc. in the balanced equation

p_A, p_B, p_C , etc. = partial pressures of the components at the assumed reaction temperature

n_A, n_B, n_C , etc. = actual molar concentrations at the assumed temperature

K_p = equilibrium pressure constant

and

K_n = equilibrium concentration constant

While mass balances are preferably written on a mole basis, thermodynamic equilibrium constants are usually expressed in terms of the partial pressures or activities of the chemical species. However, use of the equilibrium pressure constant enables all unknowns to be expressed in mole units. According to Dalton's Law,

$$p_j = \frac{n_j}{n_T} p_T \quad (173)$$

where

p_j = partial pressure of the j th product

n_j = moles of the j th product

n_T = total gaseous moles

p_T = total pressure

Then,

$$K_p = \frac{\left(\frac{n_C}{n_T} p_T\right)^c \left(\frac{n_D}{n_T} p_T\right)^d \left(\frac{n_E}{n_T} p_T\right)^e \left(\frac{n_F}{n_T} p_T\right)^f}{\left(\frac{n_A}{n_T} p_T\right)^a \left(\frac{n_B}{n_T} p_T\right)^b} \quad (174)$$

$$K_p = \frac{n_C^c \cdot n_D^d \cdot n_E^e \cdot n_F^f}{n_A^a \cdot n_B^b} \left(\frac{p_T}{n_T}\right)^{\Delta n} \quad (175)$$

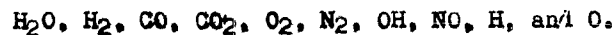
$$K_p = K_n \left(\frac{p_T}{n_T}\right)^{\Delta n} \quad (176)$$

where

Δn = the number of moles of products minus the number of moles of reactants

Knowledge of the chemical species existing at the combustion temperature is a prerequisite to making accurate performance calculations. In general, every compound that can theoretically exist will be present in some concentration and must be considered until it is proven to exist in negligible quantities. For example, in a propellant system containing

carbon, hydrogen, oxygen, and nitrogen, at least the following species must be considered as products of combustion:³⁷



The appropriate mass balances may be expressed as:

$$(1) \quad n_T = n_{\text{H}_2\text{O}} + n_{\text{H}_2} + n_{\text{CO}} + n_{\text{CO}_2} + n_{\text{O}_2} + n_{\text{N}_2} + n_{\text{OH}} + n_{\text{NO}} + n_{\text{H}} + n_{\text{O}} \quad (177)$$

$$(2) \quad n_{\text{H}} = 2n_{\text{H}_2} + 2n_{\text{H}_2\text{O}} + n_{\text{OH}} + n_{\text{H}} \quad (178)$$

$$(3) \quad n_{\text{O}} = n_{\text{H}_2\text{O}} + n_{\text{CO}} + 2n_{\text{CO}_2} + 2n_{\text{O}_2} + n_{\text{NO}} + n_{\text{OH}} + n_{\text{O}} \quad (179)$$

$$(4) \quad n_{\text{C}} = n_{\text{CO}} + n_{\text{CO}_2} \quad (180)$$

$$(5) \quad n_{\text{N}} = 2n_{\text{N}_2} + n_{\text{NO}} \quad (181)$$

The following chemical equilibria may be chosen and their equilibrium constants expressed as follows:

$$(6) \quad \text{CO}_2 + \text{H}_2 \rightleftharpoons \text{CO} + \text{H}_2\text{O}$$

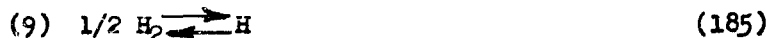
$$K_p = \frac{p_{\text{CO}} \cdot p_{\text{H}_2\text{O}}}{p_{\text{CO}_2} \cdot p_{\text{H}_2}} \quad K_n = \frac{n_{\text{CO}} \cdot n_{\text{H}_2\text{O}}}{n_{\text{CO}_2} \cdot n_{\text{H}_2}} = K_p \left[\frac{n_T}{p_T} \right]^0 \quad (182)$$

$$(7) \quad \text{H}_2\text{O} + 1/2 \text{N}_2 \rightleftharpoons \text{H}_2 + \text{NO}$$

$$K_p = \frac{p_{\text{H}_2} \cdot p_{\text{NO}}}{p_{\text{H}_2\text{O}} \cdot p_{\text{N}_2}^{1/2}} \quad K_n = K_p \left[\frac{n_T}{p_T} \right]^{1/2} \quad (183)$$

$$(8) \quad 2\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2 + \text{O}_2$$

$$K_p = \frac{p_{\text{H}_2}^2 \cdot p_{\text{O}_2}}{p_{\text{H}_2\text{O}}^2} \quad K_n = K_p \left[\frac{n_T}{p_T} \right]^1 \quad (184)$$



$$K_p = \frac{P_{\text{H}}}{P_{\text{H}_2}^{1/2}} \quad K_n = K_p \left[\frac{n_{\text{T}}}{P_{\text{T}}} \right]^{1/2}$$



$$K_p = \frac{P_{\text{H}_2}^{1/2} \cdot P_{\text{OH}}}{P_{\text{H}_2\text{O}}} \quad K_n = K_p \left[\frac{n_{\text{T}}}{P_{\text{T}}} \right]^{1/2}$$

Since ten independent equations have been expressed in ten unknowns, the product composition can be determined by simultaneous solution.

The use of specific chemical equilibria, as shown above, is quite desirable for hand calculations. However, this approach is less desirable for programming a high speed digital computer since the incorporation of a new product of combustion into the study requires a modification to the program. To avoid this, a more general equilibria approach is to utilize the equilibrium constants for the formation of each product of combustion from its monatomic gaseous species. For example,



$$K_p = \frac{P_{\text{AlCl}_3}}{P_{\text{Al}} \cdot P_{\text{Cl}}^3} = K_n \left[\frac{n_{\text{T}}}{P_{\text{T}}} \right]^3 \quad (187)$$

4. Chamber Composition Iteration

Since the previous composition calculation may involve fifty or more simultaneous equations, direct algebraic solution is not generally feasible. Therefore, some type of iterative solution is most conveniently

used, depending on the chemistry of the system. Typical methods of iteration are discussed in the literature.^{38, 39, 40} Iteration is continued until the quantity of each product converges within a pre-determined degree of accuracy, e.g. 1.0×10^{-6} gram-moles per gram of propellant.⁴¹ In view of these detailed, repetitive procedures, high-speed digital computers are profitably utilized for obtaining rapid rigorous solutions. In fact, the complexity of the problem almost dictates the use, both economically and technically, of a large digital computer, such as the IBM 704 or the Remington-Rand 1103A.

5. Enthalpy Balance

After determining the chamber composition at the assumed combustion temperature, an enthalpy balance is made. The enthalpy of the products of combustion may be obtained by integrating the energy equation

$$\left(\frac{\partial H}{\partial p}\right)_T = V - T\left(\frac{\partial V}{\partial T}\right)_p \quad (188)$$

along an isotherm between a very low pressure p^0 and any pressure p at which the gas mixture is ideal. This gives⁴²

$$H = H^0 + \int_{p^0}^p \left[V - T\left(\frac{\partial V}{\partial T}\right)_p \right] dp \quad (189)$$

and subsequently

$$H = \sum n_j H_j \quad (190)$$

where

H = enthalpy of the complex mixture

n_j = moles of the j th product

H_j = enthalpy of the j th product

The enthalpy of mixing is zero for a mixture of ideal gases. When the enthalpy of the products of combustion above a standard reference temperature equals the heat of reaction of the propellant, the adiabatic combustion temperature is defined. Mathematically,

$$-\sum n_j (H_j)_p = \Delta H_R = \sum n_j (\Delta H_{fj})_p - \sum n_j (\Delta H_{fj})_r \quad (191)$$

where

H_j = enthalpy of the j th component at 298°K
 ΔH_R = heat of reaction at 298°K
 n_j = moles of the j th component
 ΔH_{fj} = heat-of-formation of the j th component at 298K

and

p = products
r = reactants

Recombining the above equation,

$$\left[\sum n_j (H_j)_p \right]_{298}^{T_c} + \sum n_j (\Delta H_{fj298})_p = \sum n_j (\Delta H_{fj298})_r \quad (192)$$

This states that the summation of the heat-of-formation at the standard temperature plus the change in enthalpy above that temperature of all the combustion products must equal the heat-of-formation of the propellant at the standard temperature. For each assumed combustion temperature, the chamber composition and the chamber enthalpy balance must be calculated as described above. These steps are repeated until the enthalpy balance is satisfied.

6. Calculation of Chamber Entropy

After the combustion temperature, composition, and enthalpy have been defined, the entropy of the complex mixture is calculated. Each individual product of combustion contributes to the total entropy of the mixture, as in the calculation of total enthalpy. However, the direct mixing of gases at constant pressure and temperature is an irreversible process, so there is an additional entropy-of-mixing contribution. In order to evaluate this

entropy change, a reversible process must be devised so that the second law of thermodynamics applies, i.e.

$$ds = \frac{dq_r}{T} \quad (193)$$

The total work done by each gas specie as it is expanded isothermally from the initial total pressure to its equilibrium partial pressure is

$$w = -RT \sum n_j \ln n_j \quad (194)$$

per mole of mixture. By the first law,

$$\Delta E = q - w \quad (195)$$

but $\Delta E = 0$ for all isothermal changes of ideal gases. Therefore,

$$q = -RT \sum n_j \ln n_j \quad (196)$$

or

$$\Delta S = -R \sum n_j \ln n_j \quad (197)$$

Although the effect of pressure on ideal enthalpy is zero, this contribution must also be added to the total entropy. For one mole of mixture,

$$\Delta S = R \ln p_T \quad (198)$$

Combining these three contributions, the total entropy of the combustion products in the combustion chamber is

$$S_c = \sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p_T \quad (199)$$

where

S_c = chamber entropy
 n_j = moles of the j th product
 S_j = ideal entropy of the j th product at T_c
 n_T = total moles of gaseous products
 p_T = total chamber pressure
 R = universal gas constant

When solids or liquids are present as products of combustion, they are assumed to occupy no volume. Consequently, they are included in the $n_j S_j$ summation but do not contribute to the entropy of mixing or the effect of pressure on entropy. As was presented earlier, the entropy of mixing of liquid products is considered negligible.

7. Exhaust Composition Iteration

The products of combustion are expanded isentropically through the converging-diverging nozzle to an established pressure and an unknown temperature. Again, using mass balances and equilibria relationships, the exhaust composition is calculated at the exhaust pressure and an assumed exhaust temperature. As before, iteration is continued until the quantity of each product converges within a pre-determined degree of accuracy.

8. Entropy Balance

After determining the exhaust composition at the assumed exhaust temperature, an entropy balance is made. The balance is satisfied when the change in entropy between the chamber and nozzle exit is zero, i.e.

$$\left[\Delta S \right]_{T_e}^{T_c} = 0 = \left[\sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p \right]_c - \left[\sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p \right]_e \quad (200)$$

In all probability, several assumptions of temperature will have to be made before a solution is obtained. Both the exhaust composition iteration and the entropy balance are repeated until the solution is reached.

9. Exhaust Enthalpy

After determining the exhaust temperature and composition at constant entropy, the enthalpy of the exhaust products is evaluated as

$$H_e = \left[\sum n_j H_j \right]_{298}^{T_e} + \sum n_j \Delta H_{f,j298} \quad (201)$$

Previously, the enthalpy of the chamber products was evaluated as

$$H_c = \left[\sum n_j H_j \right]_{298}^{T_c} + \sum n_j \Delta H_{f,j298} \quad (202)$$

It is important to note that the n_j are the actual equilibrium concentrations of the various product species at the exhaust and chamber temperature, respectively. Thus, the total enthalpy change through the nozzle is

$$\Delta H = H_c - H_e \quad (203)$$

10. Rocket Performance Parameters

From the previously calculated properties, specific impulse is rigorously evaluated as

$$(a) \quad I_{sp} = \sqrt{\frac{2J}{g} (H_c - H_e)} \quad (204)$$

The volumetric specific impulse, the specific heat capacity, and the mean molecular weight of the products may be rigorously evaluated as

$$(b) \quad I_{vap} = \rho \cdot I_{sp} \quad (205)$$

$$(c) \quad c_p = \sum n_j c_{p_j} \quad (206)$$

$$(d) \quad MW = \frac{100 \text{ grams propellant}}{n_T} \quad (207)$$

It should be noted that 100 gm of propellant is a standard basis upon which to calculate propellant performance.

The preferred method of evaluating the other performance parameters may depend upon the nature of the propellant system. When all products of combustion are gases, the following approach is rigorous:

$$(e) \quad \frac{c_p}{c_v} = k = \frac{1}{1 - \frac{\ln T_c/T_e}{\ln p_c/p_e}} \quad (208)$$

$$(f) \quad c_F = \sqrt{\frac{4k^2}{k^2-1} \left[\frac{2}{k+1} \right]^{\frac{2}{k-1}} \left[1 - \frac{T_e}{T_c} \right]} \quad (209)$$

$$(g) \frac{A_e}{A^*} = \frac{k}{c_F} \left[\frac{2}{k+1} \right]^{\frac{k+1}{k-1}} \left[\frac{p_e}{p_e} \right]^{\frac{1}{k}} \quad (210)$$

$$(h) c^* = \frac{I_{sp} \cdot g}{c_F} \quad (211)$$

However, these equations require some adjustment when multiphase flow exists, i.e. when solids or liquids are present as products of combustion. In this case, the following approach is preferred:

$$(g) \frac{c_F}{c_T} = k = \frac{c_p}{c_p - n_T R} \quad (212)$$

$$(h) \frac{p_e A_e}{m} = \frac{1}{a} \cdot n_T \frac{T_e}{I_{sp}} \quad (213)$$

$$a = \frac{g(100 \text{ gm propellant})}{R(3.08595 \text{ ft-lb/cal}) (453.59 \text{ gm/lb})} = 1.1567 \quad (214)$$

$$(i) \frac{g}{c^*} = a^{1/2} \left[\frac{k}{n_T T_e} \right]^{1/2} \cdot \left[\frac{2}{k+1} \right]^{\frac{k+1}{2(k-1)}} \quad (215)$$

$$(j) c_T (\text{approx.}) = \frac{I_{sp} \cdot g}{c^*} \quad (216)$$

$$(k) \frac{A_e}{A^*} (\text{approx.}) = \frac{g}{c^*} \cdot \frac{p_e}{p_e} \cdot \frac{p_e A_e}{m} \quad (217)$$

Since different values of specific impulse, exhaust temperature, and specific heat ratio will exist for shifting and frozen flow, the parameters $p_e A_e / m$, c_F , and A_e / A^* will also vary. The characteristic exhaust velocity c^* can be rigorously evaluated only if throat conditions are accurately known. However, this requires some detailed point-to-point calculations. A good approximation to c^* is obtained by using the chamber temperature and specific heat ratio in the above equation.

B. Method of Minimization of Free Energy

1. General Concepts

For the determination of the equilibrium composition of a complex mixture, the only thermodynamic property required is the Gibbs' standard free energy. Earlier, this was shown to be

$$dF = Vdp - SdT \quad (218)$$

under adiabatic, reversible conditions in which all work is accomplished by expansion. This is probably the most useful combined statement of the first and second laws of thermodynamics since pressure and temperature are the independent variables. However, a more direct approach to the calculation of propellant performance may be achieved through the basic definition of free energy

$$F = H - TS \quad (219)$$

Substituting the expressions of enthalpy and entropy developed in the previous section,

$$F = \sum n_j H_j - T \sum n_j S_j + RT n_T \sum \ln \frac{n_j}{n_T} + RT n_T \ln p_T \quad (220)$$

where

F = total free energy of the combustion products
 n_j = moles of the j th product
 H_j = enthalpy of the j th product
 S_j = entropy of the j th product
 T = temperature
 R = universal gas constant
 n_T = total gaseous moles
 p_T = total pressure

The equilibrium composition may be determined by finding the set of positive values n_j which minimize the previous equation while simultaneously satisfying the mass balances.

A procedure for applying the method of the minimization of free energy to propellant performance calculations was first presented by White, Johnson, and Dantzig.⁴³ In their approach, the free energy function F/RT is minimized at constant temperature instead of utilizing equilibrium equations as was done in the previously discussed calculation method. Another feature of their approach was the derivation of the method of "steepest descent" for solving a symmetric set of linear equations by the matrix technique in the iteration procedure. Only $m + 1$ linear equations in $m + 1$ unknowns need to be solved where m represents the number of elements present in the mixture. Thus, the number of simultaneous equations to be solved is usually much smaller than the number of products of combustion. This advantage is particularly adaptable to linear programming for a large, high-speed digital computer. However, the principal limitation of the White, Johnson, and Dantzig method is that, as developed, it is applicable only to complex mixtures in which all the constituents are gases. This is unsatisfactory for the evaluation of many prototype propellant systems in which solid or liquid products of combustion are formed.

More recently, an improved technique for the minimization of free energy was developed by A. E. Roberts.⁴⁴ Instead of minimizing the free energy of a complex mixture at constant temperature, Roberts' method allows both temperature and composition to vary while maintaining either constant enthalpy or constant entropy. This method has been programmed for the Remington-Rand 1103A computer and is applicable to evaluating the equilibrium composition of complex mixtures containing solid, liquid, and gaseous constituents. Since this method was used for conducting the performance calculations presented later in this report, the important programming

concepts as well as the computational technique will be discussed in detail.

2. Establishing the Mass Balances

In programming notation, Roberts' method designates the elemental mass balance as⁴⁵

$$\sum_j A_{ij} M_j = E_i \quad (221)$$

where

i = ingredient element

j = exhaust specie

E_i = total gram-atoms of the i th element present in the propellant formulation

M_j = moles of the j th exhaust specie present in the equilibrium mixture

A_{ij} = atoms of the i th element present in the j th exhaust specie. A_{ij} must be a positive, whole integer.

The maximum possible concentration of any given specie is defined by the minimum quantity of any ingredient element that is available from any of the applicable mass balances, i.e.

$$0 \leq M_j \leq \min_i \frac{E_i}{A_{ij}} = B_j \quad (222)$$

Thus, the most restrictive mass balance defines B_j , the maximum number of moles of a given specie j which can possibly be formed. For example, the value of B_j for CO_2 would be smaller of the following:

$$0 \leq n_{\text{CO}_2} \leq \frac{\sum \text{O}}{2} = B_j \quad (223)$$

$$0 \leq n_{\text{CO}_2} \leq \sum \text{C} = B_j \quad (224)$$

For programming convenience, let $x_j = \frac{M_j}{B_j}$. Then, the mass balance may be re-stated as

$$\sum_j A_{ij} B_j x_j = E_i \quad (225)$$

or

$$\frac{\sum_j A_{ij} B_j x_j}{E_i} = 1 \quad (226)$$

Now, let

$$a_{ij} = \frac{A_{ij}}{E_i} B_j = \frac{A_{ij}}{E_i} \min \frac{E_i}{A_{ij}} = \frac{\min \frac{E_i}{A_{ij}}}{\frac{E_i}{A_{ij}}} \quad (227)$$

Both x_j and a_{ij} vary in value between 0 and 1.

Thus, the mass balance may be expressed in standard normalized form as

$$\sum_j a_{ij} x_j = 1 \quad (228)$$

for which the coefficients a_{ij} are stored in matrix form. The quantities x_j are proportional to the mole fraction of the respective exhaust species.

The total moles of gas are expressed as

$$M_o = \sum_{j=1}^{m+n} M_j \quad (229)$$

where

m = gaseous elements
 n = gaseous molecules
 p = condensed phases

The maximum possible number of gaseous moles would occur if the entire propellant formulation existed as gaseous elements. Thus, the limits for M_o are

$$0 < M_o < \sum E_i = B_o \quad (230)$$

Letting $M_o = B_o x_o$,

$$B_o x_o = \sum_{j=1}^{m+n} B_j x_j \quad (231)$$

or

$$x_o = \sum_{j=1}^{m+n} \frac{B_j}{B_o} x_j \quad (232)$$

The quantity x_o is another programming convenience which varies in value between 0 and 1. It should also be noted that $B_j x_j$ represents the moles of

any species j present in the equilibrium mixture while $B_0 x_0$ represents the total gaseous moles at any one time. From Dalton's Law, the partial pressure contributed by each gaseous specie j is

$$p_j = \frac{x_j B_j}{x_0 B_0} p_T \quad (233)$$

where B_j , B_0 , and p_T remain constant while x_0 and x_j are variables.

The various x_j 's indicate the degree to which a specie contributes to completing each mass balance. To insure operability, the x_j 's are ordered in magnitude for each trial solution, i.e. all species j which contain element i are listed in order of decreasing concentration. Since the x_j 's are proportional to the mole fraction of each respective specie j , this ordering procedure establishes priority for choosing a basis upon which to define the dependent variables. The species possessing the greatest x_j are chosen as the basic variables, with these species being selected as the basis in the mass balance for which they possess the greatest A_{ij} . For example, any concentration of CO_2 contributes more to the oxygen balance than to the carbon balance. Thus, CO_2 would be considered as a basis only in the oxygen balance. Then, it could be eliminated from the carbon balance. In this manner, a set of majors and minors is inherently established, i.e. a limited number of dependent basis variables are chosen while the remaining species are independent variables. The number of basis variables is limited to the number of elements in the propellant formulation. The concentration of any of the independent variables may be changed by an arbitrary amount. Then, the concentrations of the basis variables are determined from the mass balances and the concentrations of the independent variables. When the order of priority changes, the basis is revised. Both the mass balance equations

and the total gaseous moles equation are maintained throughout the transformations of the matrices. Previously, the free energy equation was written

$$F = \sum n_j H_j - T \sum n_j S_j + RT n_T \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + RT n_T \ln p_T \quad (234)$$

Incorporating the program notation, this becomes

$$F = \sum_{j=1}^{m+n+p} H_j (B_j x_j) - T \sum_{j=1}^{m+n+p} S_j (B_j x_j) + RT \sum_{j=1}^{m+n} (B_j x_j) \ln \frac{B_j x_j}{B_o x_o} + RT \sum_{j=1}^{m+n} B_j x_j \ln p_T \quad (235)$$

or

$$F = \sum_{j=1}^{m+n+p} B_j x_j (H_j - TS_j) + RT \sum_{j=1}^{m+n} B_j x_j (\ln B_j x_j) + RT B_o x_o \left(\ln \frac{p_T}{B_o x_o} \right) \quad (236)$$

where

F = molar free energy
H = molar enthalpy
S = molar entropy
T = temperature
n_j = moles of exhaust specie j
B_j = maximum possible moles of specie j
x_j = ratio of actual moles of specie j to the maximum number of moles of specie j
R = universal gas constant
n_T = total gaseous moles
B_o = maximum possible total moles of gas
x_o = ratio of actual total moles of gas to the maximum number of moles of gas
p_T = total pressure
m = gaseous elements
n = gaseous molecules
p = condensed phases

3. Thermodynamic and Computational Approach

From the basic relationship

$$dF = V dp - S dT \quad (237)$$

it follows that, for an ideal gas,

$$\left[\frac{\partial F}{\partial T} \right]_p = -S \quad (238)$$

For a mixture of ideal gases, the additional restriction of constant concentration must be applied to the previous equation. This may also be shown from the definition of free energy

$$F = H - TS \quad (239)$$

Then,
$$\frac{dF}{dT} = \frac{dH}{dT} - T\frac{dS}{dT} - S \quad (240)$$

$$\frac{dF}{dT} = C_p - T\frac{dS}{dT} - S \quad (241)$$

However,
$$\frac{dS}{dT} = \frac{C_p}{T} \quad (242)$$

Therefore,
$$\frac{dF}{dT} = -S < 0 \quad (243)$$

$$\frac{d^2F}{dT^2} = -\frac{dS}{dT} = -\frac{C_p}{T} < 0 \quad (244)$$

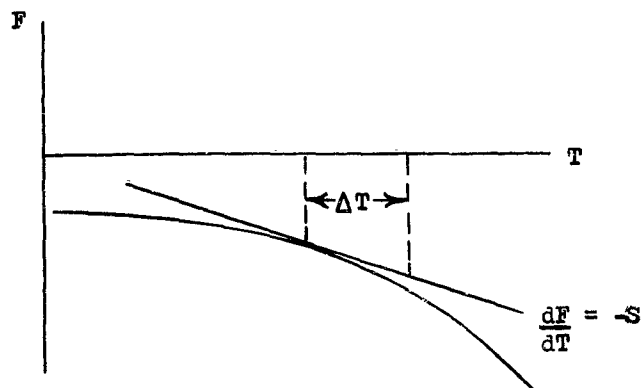
These equations express the effect of a change in temperature on the ideal free energy of a complex mixture at constant pressure and concentration.

The first derivative $\frac{dF}{dT}$ measures the slope of the free energy curve while the

second derivative $\frac{d^2F}{dT^2}$ measures the curvature. Both the slope and the change

in slope are always negative with the second derivative being numerically smaller than the first. Therefore, the curvature is always concave downward.

The slope of the free energy curve is a good approximation to the actual curve over a fairly wide range of temperature. Furthermore, this approximation is a conservative one in that the tangent to the curve always lies above the actual curve, as illustrated below:



$$F(T + \Delta T) \leq F(T) - S(T) \Delta T \quad (245)$$

$$\Delta F \leq -S(T) \Delta T \quad (246)$$

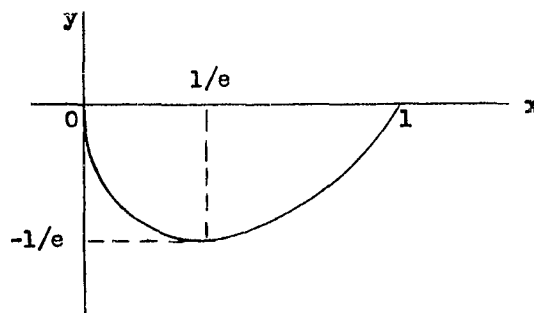
Thus, free energy may be readily estimated over small temperature intervals by the first derivative. It is important to note that these equations apply rigorously only to the ideal free energy at one atmosphere pressure. Neither the effect of mixing nor the effect of pressure is included. Whereas changes in the partial molal free energy arise from changes in temperature, changes in the entropy of mixing and pressure arise from changes in concentration.

Both of these latter quantities may be incorporated into the total free energy summation through the use of a supplemental equation of the form

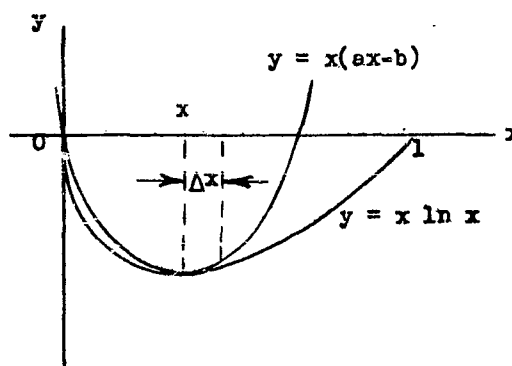
$$y = x \ln x \quad (247)$$

where y = free energy of mixing and pressure
 x = concentration of the various gaseous species

For the normalized form of the equation where $0 \leq x \leq 1$, the absolute minimum y occurs at $x = 1/e$ and has the value $y = -1/e$, where e is the base of natural logarithms.



The slope at the y-axis is infinite while the curve intersects the x-axis at 0 and 1. Since the calculation of the $x \ln x$ function is a relatively lengthy procedure on a digital computer, Roberts has developed a quick approximation which permits a reasonable decrease in free energy for a modest calculational effort.⁴⁶ This approximation is made by constructing a parabola which is tangent to the $y = x \ln x$ curve at the initial point x and which passes through the origin, as shown below:



This is also a conservative approximation since the change in free energy is never as great on the parabola as on the $x \ln x$ curve except at the point of tangency. One such approximation is made for each specie at each trial composition. Furthermore, 100% convergence is mathematically guaranteed.

For the true free energy curve

$$y = x \ln x \quad (248)$$

and

$$\frac{dy}{dx} = \ln x + 1 \quad (249)$$

while for the parabolic approximation

$$y = x(ax - b) \quad (250)$$

and

$$dy/dx = 2ax - b \quad (251)$$

combining these into two simultaneous equations,

$$x \ln x = ax^2 - bx \quad (252)$$

$$x(\ln x + 1) = 2ax^2 - bx \quad (253)$$

the constants are found to be

$$a = \frac{1}{x} \quad (254)$$

$$b = 1 - \ln x \quad (255)$$

Using this approach, the approximate change in $y = x \ln x$ corresponding to a change in x is

$$(y + \Delta y) = (x + \Delta x) \ln (x + \Delta x) \leq (x + \Delta x) \left[\frac{x + \Delta x}{x} - 1 + \ln x \right] \quad (256)$$

$$(y + \Delta y) \leq (x + \Delta x) \left(\frac{\Delta x}{x} + \ln x \right) \quad (257)$$

$$\Delta y = \Delta(x \ln x) \leq \Delta x \left[1 + \ln x + \frac{\Delta x}{x} \right] \quad (258)$$

It is important to note that x , the concentration variable, is actually the quantity $B_j x_j$ used in the program notation. Also, during the progress of a calculation, both T and x are interim numbers. The Δ values are the amounts of change employed in the next trial solution. Changes in concentration are always made for one specie at a time, choosing that specie which will reflect

the greatest change in the total free energy of the system. For each change in concentration, there is a corresponding change in temperature, and vice versa. By conducting a number of small, incremental changes, the free-energy of the system is rapidly minimized with a minimum of calculational effort.

4. Details of the Calculation Method

The calculational routine is initiated by assuming that the entire propellant composition exists as monatomic gases. This, of course, is a hypothetical situation which defines the maximum free energy and the maximum total moles of gaseous products for the system. Also, at constant enthalpy, the corresponding temperature of the monatomic gas mixture is a very low hypothetical one. In turn, the various products of combustion are introduced incrementally into the complex mixture. Each addition serves to reduce the free energy and increase the temperature of the mixture until equilibrium is attained. As shown previously, the free energy of a mixture of combustion products is

$$F = \sum_{j=1}^{m+n+p} n_j (H_j - TS_j) + RTn_T \left[\sum_{j=1}^{m+n} \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln p_T \right] \quad (259)$$

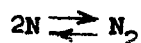
For a single gaseous specie of the mixture, the free energy is

$$F = \sum_{j=1}^{m+n} n_j (H_j - TS_j + RTn_j \ln n_j) + RT n_T \ln \frac{p_T}{n_T} \quad (260)$$

where

F = free energy
H = enthalpy
S = entropy
T = temperature
n_j = moles of specie j
R = universal gas constant
p_T = total pressure
n_T = total moles of gaseous products
m = gaseous elements
n = gaseous molecules
p = condensed phases

For any incremental change in the concentration of the combustion products, there will be three contributions to the change in free energy of the mixture: (1) the free energy contributed by the formation of the new product; (2) the free energy lost by the decrease in concentration of the reactant(s); and (3) the free energy change introduced by the variation in the total number of gaseous moles. The method of handling these changes in the calculational approach may be best shown by an example. Consider the formation of nitrogen gas from its atoms:



$$\Delta n_N = -2\Delta n_{N_2} \quad (261)$$

$$\Delta n_T = \Delta n_N + \Delta n_{N_2} = -\Delta n_{N_2} \quad (262)$$

A change in the number of moles of N_2 creates an inherent change in the number of moles of N . At a given temperature and concentration, the free energy of the mixture may be expressed as

$$F = n_N \left[H_N(T) - TS_N^\circ(T) \right] + RT n_N \ln n_N + n_{N_2} \left[H_{N_2}(T) - TS_{N_2}^\circ(T) \right] + RT n_{N_2} \ln n_{N_2} + \dots + RT n_T \ln \frac{p_T}{n_T} \quad (263)$$

Since constant enthalpy must be maintained, any change in concentration will necessitate a change in temperature of the mixture. Over a short temperature range, $c_p \Delta T \cong \Delta H$.

Therefore,

$$\Delta H = 0 = \Delta n_{N_2} \left[H_{N_2}(T) - 2H_N(T) \right] + \sum n_j c_{p_j} \Delta T \quad (264)$$

and

$$\Delta T = - \left[\frac{H_{N_2} - 2H_N}{\sum n_j c_{p_j}} \right]^T \Delta n_{N_2} \quad (265)$$

Thus, a coefficient is obtained which relates the change in temperature of the mixture to the change in concentration of an individual specie. The incremental free energy change created by a decrease in the concentration of N is

$$\Delta F = n_N \left[H_N - TS_N \right]_T^{T+\Delta T} - 2\Delta n_{N_2} \left[H_N - TS_N \right]_T^{T+\Delta T} \quad (266)$$

$$+ R(T+\Delta T) \left[(n_N - 2\Delta n_{N_2}) \ln (n_N - 2\Delta n_{N_2}) - n_N \ln n_N \right] + R \cdot \Delta T (n_N \ln n_N)$$

This includes the ideal free energy and the free energy of mixing. Similarly, the incremental change in free energy caused by the formation of N_2 is

$$\Delta F = n_{N_2} \left[H_{N_2} - TS_{N_2} \right]_T^{T+\Delta T} + \Delta n_{N_2} \left[H_{N_2} - TS_{N_2} \right]_T^{T+\Delta T} \quad (267)$$

$$+ R(T+\Delta T) \left[(n_{N_2} + \Delta n_{N_2}) \ln (n_{N_2} + \Delta n_{N_2}) - n_{N_2} \ln n_{N_2} \right] + R \cdot \Delta T (n_{N_2} \ln n_{N_2})$$

Finally, the incremental change in free energy due to the variation in total moles of products is

$$\Delta F = R(T + \Delta T) (n_T - \Delta n_{N_2}) \ln \frac{p_T}{n_T - \Delta n_{N_2}} - RT n_T \ln \frac{p_T}{n_T} \quad (268)$$

However, this may be more conveniently re-stated as

$$\Delta F = -R(T + \Delta T) (\Delta n_{N_2}) \ln p_T + R \cdot \Delta T n_T \ln \frac{p_T}{n_T} + R(T + \Delta T) \left[n_T \ln n_T - (n_T - \Delta n_{N_2}) \ln (n_T - \Delta n_{N_2}) \right] \quad (269)$$

Now, by applying the ΔF approximations previously developed, a number of coefficients may be obtained which are functions of ΔT and Δn . However, since $\Delta T = K' \Delta n$, the approximate change in free energy may be reduced to a cubic function of Δn .

First, consider the ideal contribution to free energy. From the curve of free energy versus temperature at constant concentration,

$$\Delta F = F^{\circ}(T + \Delta T) - F^{\circ}(T) \leq -S^{\circ}(T) \Delta T \quad (270)$$

Therefore,

$$n_N(-S_N^{\circ})_T \Delta T + n_{N_2}(-S_{N_2}^{\circ})_T \Delta T$$

constitutes a contribution to the total change in free energy. This contribution is the product of a constant and ΔT . Also,

$$F^{\circ}(T + \Delta T) \leq F^{\circ}(T) - S^{\circ}(T) \Delta T \quad (271)$$

Therefore,

$$-2 \Delta n_{N_2} (F_N^{\circ})_T + \Delta n_{N_2} (F_{N_2}^{\circ})_T$$

and

$$-2 \Delta n_{N_2} (-S_N^{\circ})_T \Delta T + \Delta n_{N_2} (-S_{N_2}^{\circ})_T \Delta T$$

are also contributions to ΔF .

Second, the entropy of mixing will be considered. From the parabolic approximation to the function $y = x \ln x$,

$$\Delta(x \ln x) \leq \Delta x \left[1 + \ln x + \frac{\Delta x}{x} \right] \quad (272)$$

Therefore,

$$\begin{aligned} \Delta F \leq & R(T + \Delta T) (-2 \Delta n_{N_2}) \left[1 + \ln n_N - \frac{2 \Delta n_{N_2}}{n_N} \right] + R(n_N \ln n_N) \Delta T \quad (273) \\ & + R(T + \Delta T) (\Delta n_{N_2}) \left[1 + \ln n_{N_2} + \frac{\Delta n_{N_2}}{n_{N_2}} \right] + R(n_{N_2} \ln n_{N_2}) \Delta T \end{aligned}$$

From this expression, the following additional contributions to the change in free energy are obtained:

$$(1) R(n_N + \ln n_N) \Delta T + R(n_{N_2} \ln n_{N_2}) \Delta T$$

$$(2) \quad RT(-2 \Delta n_{N_2}) (1 + \ln n_N) + RT (\Delta n_{N_2}) (1 + \ln n_{N_2})$$

$$(3) \quad RT(-2 \Delta n_{N_2}) \frac{(-2 \Delta n_{N_2})}{n_N} + RT (\Delta n_{N_2}) \frac{(\Delta n_{N_2})}{n_{N_2}}$$

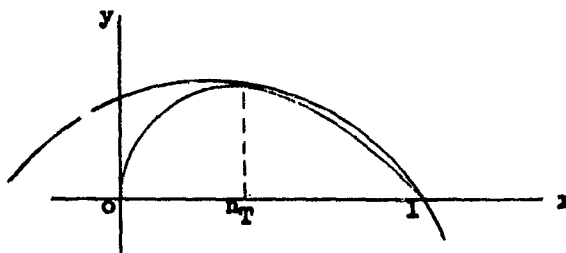
$$(4) \quad R \cdot \Delta T (-2 \Delta n_{N_2}) (1 + \ln n_N) + R \cdot \Delta T (\Delta n_{N_2}) (1 + \ln n_{N_2})$$

$$(5) \quad R \cdot \Delta T (-2 \Delta n_{N_2}) \frac{(-2 \Delta n_{N_2})}{n_N} + R \cdot \Delta T (\Delta n_{N_2}) \frac{(\Delta n_{N_2})}{n_{N_2}}$$

Finally, consider the effect of a change in the total moles of gas on the free energy. This contribution contains a term of the general form $-\Delta(x \ln x)$ where $x = n_T$ and $\Delta x = -\Delta n_{N_2}$. Because of the minus sign, the same approximation used in the entropy of mixing contribution will not apply here. The desired quadratic must satisfy the requirement

$$-\Delta(x \ln x) = \Delta(-x \ln x) \leq \text{quadratic in } \Delta x \quad (274)$$

as shown by the illustration



This inverted quadratic approximation becomes

$$\Delta F \leq R(T + \Delta T) \left[-(\ln n_T + 1) (\Delta n_T) + \frac{(n_{T_{\max}} - n_T) \div n_{T_{\max}} \ln \frac{n_T}{n_{T_{\max}}}}{(n_{T_{\max}} - n_T)^2} (\Delta n_T)^2 \right] \quad (275)$$

By applying L' Hospital's principle, the coefficient of $(\Delta n_T)^2$ becomes $-1/2$ when $n_{T_{\max}} = n_T$. Thus, the following contributions to free energy arise from the effect of total moles:

$$(1) \quad -RT (\Delta n_T) \ln p_T$$

$$(2) -R \cdot \Delta T (\Delta n_T) \ln R_T$$

$$(3) +R \cdot \Delta T n_T \ln R_T/n_T$$

$$(4) -RT (\ln n_T + 1) \Delta n_T$$

$$(5) -R \cdot \Delta T (\ln n_T + 1) \Delta n_T$$

$$(6) +RT \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2} (\Delta n_T)^2$$

$$(7) +R \cdot \Delta T \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{RT}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2} (\Delta n_T)^2$$

Now, the total incremental change in free energy, as a function of temperature and concentration may be represented by

$$\Delta F(T, x) \leq \sum_j \left[A_j' \Delta T + B_j' \Delta x_j + C_j' \Delta x_j \Delta T + D_j' (\Delta x_j)^2 + E_j' (\Delta x_j)^2 \Delta T \right] \quad (276)$$

However, utilizing the approximation

$$T = k' \Delta x \quad (277)$$

the above equation reduces to one with only three coefficients and one unknown:

$$\Delta F \leq \sum_j \left[A_j' \Delta x_j + B_j' (\Delta x_j)^2 + C_j' (\Delta x_j)^3 \right] \quad (278)$$

The value of Δx which minimizes ΔF is found by differentiating this equation and setting the derivative equal to zero:

$$\Delta x = \frac{-B_j' + \sqrt{(B_j')^2 - 3 A_j' C_j'}}{3 C_j'} \quad (279)$$

Thus, a conservative approximation has been developed which can be solved directly to give Δx . Furthermore, the true change in free energy exceeds

that found by this approximate solution. In order to maintain the mass balances, the concentration of any specie cannot become negative. At the same time, the concentration cannot exceed the maximum defined by the mass balances. These two restrictions serve as limits for the values of x found from the solution of the cubic. As equilibrium is approached, the approximate solution comes closer to and finally coincides with the rigorous evaluation of composition, temperature, and free energy. In initiating the parabolic approximation, it is assumed that $x = 2/3 x_{\max}$ instead of $x = 0$ so that the constants a and b will be finite in value. The position $x = 2/3 x_{\max}$ is the point of tangency for which, on the average, the parabolic curve best approximates the $y = x \ln x$ curve. The important concept is to utilize a parabola which always lies above the $y = x \ln x$ or the $y = -x \ln x$ curves.

The summation of the various contributions to an incremental change in free energy yields, for the $2N \rightleftharpoons N_2$ example, the following values for the constants of the cubic equation:

$$A' = \sum k' n_j (-S_j^0)_T + \sum k' R (n_j \ln n_j) - 2(F_N^0)_T + (F_{N_2}^0)_T - 2RT (1 + \ln n_N) + RT (1 + \ln n_{N_2}) - RT (\ln n_T + 1) - RT \ln p_T + k' R n_T \ln \frac{p_T}{n_T} \quad (280)$$

$$B' = \frac{A' RT}{n_N} + \frac{RT}{n_{N_2}} - 2k' (-S_N^0)_T + k' (-S_{N_2}^0)_T - 2k' R (1 + \ln n_N) + k' R \quad (281)$$

$$(1 + \ln n_{N_2}) - k' R (\ln n_T + 1) - k' R \ln p_T + RT \frac{(n_{T\max} - n_T) + n_{T\max} \ln \frac{n_T}{n_{T\max}}}{(n_{T\max} - n_T)^2}$$

$$C' = \frac{A' k' R}{n_N} + \frac{k' R}{n_{N_2}} + k' R \frac{(n_{T\max} - n_T) + n_{T\max} \ln \frac{n_T}{n_{T\max}}}{(n_{T\max} - n_T)^2} \quad (282)$$

5. Introduction of Thermodynamic Data

Thermodynamic data for the various products of combustion are conveniently introduced in equation form as a function of temperature over a specified temperature interval. Of course, reference values of enthalpy and entropy are also introduced at a reference temperature within each interval. In order to insure an accurate fit of the thermodynamic data over the complete range from 298°K to 6000°K, several equations may be utilized, if necessary. However, in general two equations are sufficient to provide a highly accurate fit. Over the low temperature range from 298°K to about 1200°K to 1500°K, specific heat capacity data are expressed as an ascending polynomial of the form

$$C_p = a + bT + cT^2 + dT^3 + eT^4 \quad (283)$$

From this, the enthalpy, entropy, and free energy of the individual species are evaluated as

$$H = \int C_p dT = H' + aT + \frac{bT^2}{2} + \frac{cT^3}{3} + \frac{dT^4}{4} + \frac{eT^5}{5} \quad (284)$$

$$S' = \int C_p \frac{dT}{T} = S' + a \ln T + bT + \frac{cT^2}{2} + \frac{dT^3}{3} + \frac{eT^4}{4} \quad (285)$$

$$F' = H - TS' = H' - TS' + aT(1 - \ln T) - \frac{bT^2}{2} - \frac{cT^3}{6} - \frac{dT^4}{12} - \frac{eT^5}{20} \quad (286)$$

where

H = enthalpy at any general temperature T

S = entropy at any general temperature T

F = free energy at any general temperature T

C_p = specific heat capacity at any general temperature T

H' = reference enthalpy

S' = reference entropy

T = temperature $\times 10^{-3}$

a, b, c, d, e = empirical constants for the curve fit

Over the high temperature range extending from about 1200°K to 1500°K, the specific heat capacity data are expressed as a descending polynomial of the form

$$C_p = a + bT^{-1} + cT^{-2} + dT^{-3} + eT^{-4} \quad (287)$$

Then, the enthalpy, entropy, and free energy equations over this interval become

$$H = \int C_p dT = H' + aT + b \ln T - \frac{c}{T} - \frac{d}{2T^2} - \frac{e}{3T^3} \quad (288)$$

$$S^\circ = \int \frac{C_p dT}{T} = S' + a \ln T - \frac{b}{T} - \frac{c}{2T^2} - \frac{d}{3T^3} - \frac{e}{3T^4} \quad (289)$$

$$F^\circ = H - TS^\circ = H' - TS' + (aT-b)(1-\ln T) - \frac{c}{2T} - \frac{d}{6T^2} - \frac{e}{12T^3} \quad (290)$$

Although any reference temperature within the corresponding temperature interval may be utilized, 298°K and 3000°K, respectively, were chosen as convenient references for most species. The former is particularly desirable since it is a standard reference for many experimental data. By using the two reference points, dual integration is not necessary over both ranges of the heat capacity curve.

The functional method of introducing data into the calculation has both a thermodynamic and a programming advantage. Since the equation constants and the reference data are known, temperature and composition are the only variables involved in the calculation of enthalpy, entropy, or free energy. For a trial composition, temperature may be computed directly at either constant enthalpy or entropy. The programming advantage arises from the great saving in data storage and from the rapid solution of a polynomial equation on a high-speed digital computer. The actual storage of tables of thermodynamic data at 100°K temperature intervals would be quite cumbersome. Furthermore, the process of table look-up and interpolation is slower than the calculation of point properties from the polynomial equation.

6. Evaluation of Thermodynamic Properties and Performance Parameters

After evaluating the chamber temperature and composition by the minimization of free energy, the entropy of the system is calculated as was done in the method of equilibrium constants. Then, the exhaust temperature and composition are evaluated by minimizing the free energy of the system at constant entropy, and the exhaust enthalpy is calculated. From these data, the various performance parameters are calculated in the same manner as for the method of equilibrium constants.

CHAPTER V

THE THEORETICAL ANALYSIS PROGRAM

A Selection of Prototype Propellant Systems for Evaluation

The object of the theoretical calculation work presented in this report is to evaluate the performance of several prototype rocket fuels and oxidizers. In general, good fuels and oxidizers should possess relatively endothermic heats-of-formation and yield combustion products with large exothermic heats-of-formation. Furthermore, only the most exothermic chemical reactions are worthy of consideration for application to rocket propulsion. Since the most exothermic reactions occur between the elements in the upper-left and the upper-right corners of the periodic table, this study was confined to fuels and oxidizers consisting of the elements carbon, hydrogen, oxygen, nitrogen, chlorine, fluorine, lithium, beryllium, boron, aluminum, and magnesium. The following prototype materials were chosen for evaluation:

Fuels

Name	Formula	Name	Formula
Liquid Hydrogen	H ₂	Liquid Oxygen	O ₂
Hydrazine	N ₂ H ₄	Liquid Fluorine	F ₂
Unsymmetrical Dimethyl Hydrazine	C ₂ N ₂ H ₈	Oxygen Difluoride	OF ₂
Polyethylene	CH ₂	100% Hydrogen Peroxide	H ₂ O ₂
Dicyanoacetylene	C ₄ N ₂	Nitrogen Tetroxide	N ₂ O ₄
Pentaborane	B ₅ H ₉	Nitrogen Trifluoride	NF ₃
Aluminum Hydride	AlH ₃	Chlorine Trifluoride	ClF ₃
Beryllium Hydride	BeH ₂	Perchloryl Fluoride	ClO ₃ F
Lithium Hydride	LiH	Nitronium Perchlorate	NO ₂ ClO ₄
Magnesium Hydride	MgH ₂	Ammonium Perchlorate	NH ₄ ClO ₄

These materials were chosen in order to obtain the maximum amount of basic information for a modest calculational effort. By evaluating several fuels with a given oxidizer, a relative order-of-merit may be established for the fuels. Similarly, the evaluation of several oxidizers with each fuel reveals the relative merits of the oxidizers. Each of the previously mentioned fuels was evaluated with each of the oxidizers. While only oxygen and fluorine were considered worthy of general study as oxidizers, five light metals, in addition to carbon and hydrogen, were considered as prime fuel ingredients. The elements nitrogen and chlorine were essentially considered as carrier elements.

The study was established systematically to reveal the effects of various fundamental chemical moieties on overall performance. For example, the interactions of the fuel groups N-H, C-H, C-N-H, Al-H, B-H, Li-H, Be-H, and Mg-H are evaluated with the oxidizer groups N-F, O-F, Cl-F, Cl-O-F, N-O, Cl-O and H-O. All calculations were conducted in accordance with the assumptions and procedures discussed earlier. For each fuel-oxidizer combination, several mixture ratios were evaluated in order to define the optimum performance and provide some indication of the influence of propellant composition on performance. Although many of the fuel-oxidizer combinations in this report are not workable propellant combinations, this approach satisfies the objective of obtaining basic theoretical combustion information.

B. Thermodynamic Properties of Reactants and Products of Combustion

1. General Thermodynamic Requirements

When performance calculations are conducted rigorously as described previously in the method of equilibrium constants and the method of minimization of free energy, the accuracy of the results is governed by the accuracy of the basic thermodynamic data utilized. For reactants, only the heat-of-formation at a reference temperature must be known. However, this quantity must be known accurately because of its importance in the enthalpy balance. If either volumetric specific impulse or ideal boost velocity is to be calculated, the density of the reactants must also be known. For products of combustion, additional thermodynamic data must be available. Both the entropy and enthalpy must be known as a function of temperature in addition to the standard heat-of-formation. With these data, a consistent set of thermodynamic functions can be computed. Usually, the conventional thermodynamic functions of C_p , S , $-(F-H_{298})/T$, $H - H_{298}$, and $H-H_{298}/T$ are tabulated at temperature intervals of 100°K . Sometimes the heat-of-formation, free-energy-of-formation, and equilibrium-constant-of-formation are also included in the same tabulation.

The availability of accurate thermodynamic data for application to rocket combustion studies deserves some special comment. As shown by the performance calculations, combustion temperatures of 3000°K - 4000°K are common. These obviously exceed the temperature range of experimental studies and require the use of thermodynamic data which have been computed from statistical mechanics. When the molecular structure and the basic molecular translational,

rotational, vibrational, and electronic contributions are known, the statistical mechanical approach is quite accurate. However, a fundamental problem in high temperature thermodynamics is molecular stability. New species which are insignificant or unknown at room temperatures may be quite stable in high temperature complex mixtures. An example of this phenomenon is metaboric acid, HBO_2 , which replaces B_2O_3 as the dominant boric species in the B-O-H system above 2000°K . Frequently, insufficient data are available on the high temperature decomposition and chemical equilibria of species which are quite stable at lower temperatures. This shortcoming can only be resolved by experimental research.

2. Heat-of-Formation of Reactants

The standard heats-of-formation for the reactants used in this theoretical study are, for the most part, quite accurately known. These are listed along with the densities of the reactants in Table I. Only the heats-of-formation of AlH_3 and BeH_2 are reasonably in doubt. Since these two hydrides have not been prepared in pure quantities, accurate experimental heat-of-formation data are lacking. Estimates of the ΔH_f of AlH_3 and BeH_2 vary from between +20 Kcal/mole and -15 Kcal/mole. Whereas the corresponding hydrides of lithium and magnesium are readily synthesized from the elements, attempts to prepare AlH_3 and BeH_2 in this manner have been unsuccessful. These data, along with the Al-H and Be-H bond strengths, indicate that the ΔH_f of both hydrides should be endothermic. Therefore, a ΔH_f of +10 Kcal/mole was chosen for AlH_3 , and a ΔH_f of +10 Kcal/mole was also selected for BeH_2 .

TABLE I

HEATS-OF-FORMATION AND DENSITIES OF REACTANTS

Reactant	Heat-of-formation Kcal/mole	Density g/cc	Ref. Temp. °K	State
H ₂	-1.887	0.071	20.4	Liquid
N ₂ H ₄	+12.05	1.004	298.16	Liquid
C ₂ N ₂ H ₈	+12.74	0.786	298.16	Liquid
CH ₃	-6.50	0.920	298.16	Solid
C ₄ N ₂	+118.0	0.970	298.16	Liquid
B ₅ H ₉	+7.74	0.620	298.16	Liquid
AlH ₃	+10.0*	1.72*	298.16	Solid
BeH ₂	+10.0*	Unknown	298.16	Solid
LiH	-21.6	0.820	298.16	Solid
MgH ₂	-17.9	1.45	298.16	Solid
O ₂	-3.08	1.14	90.2	Liquid
F ₂	-3.47	1.51	85.2	Liquid
OF ₂	+3.6	1.53	128.0	Liquid
H ₂ O ₂	-44.84	1.443	298.16	Liquid
N ₂ O ₄	-5.4	1.43	298.16	Liquid
NF ₃	-32.2	1.532	144.0	Liquid
ClF ₃	-44.4	1.819	298.16	Liquid
ClO ₂ F	-10.1	1.43	298.16	Liquid
NO ₂ ClO ₄	+8.0	2.22	298.16	Solid
NH ₄ ClO ₄	-69.42	1.96	298.16	Solid

* Estimated Values

3. Thermodynamic Properties of Combustion Products

The current status of the thermodynamic properties of combustion products varies from excellent, as in the case of hydrogen gas, to purely theoretical, as in the case of such metallic oxyhalides as AlOCl . In most cases, the properties of the dominant species are reasonably well defined for engineering applications. This is particularly true for products of combustion formed from the elements carbon, hydrogen, oxygen, nitrogen, chlorine, and fluorine. These data have been reported by Huff, et. al.,⁴⁷ Gordon⁴⁸, Stull and Sinke⁴⁹, Rossini, et. al.,⁵⁰ and others. In general, somewhat less is known about the thermodynamic properties of combustion products containing the metals lithium, boron, beryllium, magnesium, and aluminum. However, two relatively recent reports by Evans, Prosen, and Wagnon provide a thorough summary of the properties of boron compounds.^{51, 52} Still another recent report by Beckett, et. al., provides a summary of the known thermodynamic properties of lithium, beryllium, aluminum, and magnesium and their compounds with oxygen, hydrogen, fluorine, and chlorine.⁵³ Additional compilations of thermodynamic functions have been made by Gordon^{54, 55}, Stull and Sinke⁵⁶, Henderson, et. al.,^{57, 58} and others which are applicable to the performance calculations presented in this report as well as to calculations involving other elements. All thermodynamic data used in this report are summarized in Table II, III, and IV at the end of this section. In Table II, standard values of heat-of-formation and entropy are summarized at reference temperatures. Constants for the heat capacity equation

$$C_p = a + bT + cT^2 + dT^3 + eT^4 \quad (291)$$

are presented in Table III and constants for the heat capacity equation

$$C_p = a + bT^{-1} + cT^{-2} + dT^{-3} + eT^{-4} \quad (292)$$

are presented in Table IV. These curve fits were provided by Messrs. C.B.

Henderson and R. S. Scheffer.⁵⁹ Unless otherwise specified by subscript, all species listed in Tables II, .II, and IV are gaseous molecules.

In somewhat more detail, the current status of the thermodynamic data on the metal-containing species may be summarized for various temperature ranges. From 0°K to 1000°K, experimental data are rather complete and fairly accurate for the species stable over this temperature range. Heats-of-formation and heat capacities have been measured for practically all of the significant solids and liquids. However, the chemical instability of the hydrides and the hydroxides, with the exception of LiOH, has precluded accurate measurement of their vapor pressures and heats of vaporization.⁶⁰ Low volatility of some other compounds has hindered vapor-phase studies in this temperature range.

Experimental difficulties increase in the range of 1000°-2000°K, but these are not sufficiently formidable to prevent most thermodynamic measurements. Specific heat capacity data are complete for some refractory materials, such as MgO, but usually do not extend to the melting point for substances which melt between 1000°K and 2000°K, such as Li₂O.⁶¹ The availability of vapor-condensed phase equilibrium data for the stable species helps to compensate for lack of other data. The newer techniques of optical and mass spectrometry and molecular beams have greatly assisted in identifying the composition of high temperature gas mixtures.⁶² However, more accurate analyses of such mixtures is needed. Experimental heat-of-fusion data are needed on most compounds.

Above 2000°K there are very little data on condensed phases. Specific heat capacities have been extrapolated from lower temperatures. Thermodynamic

properties of the gas species are quite accurately known for the monatomic and many of the diatomic species. However, in the polyatomic species and some of the diatomic species, molecular constant data are needed. Also, dissociation energies need refinement in most cases.⁶³

A number of polyatomic gas species have been observed at low pressures by vaporization of solids and liquids in mass spectrometers. In a few cases, the electron-diffraction and infra-red spectra are also available. However, the configuration and molecular constants have been established with reliability for only a few of these species.

Basic low temperature data are available on the more significant aluminum compounds, such as Al_2O_3 , AlCl_3 , and AlF_3 . At high temperatures, the existence of AlF_2 and AlCl_2 has been proposed on the basis of indirect evidence. Also, the oxyhalides AlOF and AlOCl and the interhalides AlF_2Cl , AlFCl_2 , and AlFCl may be stable molecules, although no direct evidence for their existence is available. These molecules were first proposed by Gordon.⁶⁴ Their fundamental vibrations and bond distances have been estimated from values for related molecules.⁶⁵ Equilibrium studies of the Al-O system indicate that Al_2O is the predominant vapor species and that Al_2O_3 does not exist as a gas. The heat-of-formation and stability of crystalline aluminum nitride are probably the most questionable of the light metal nitrides. Experimental heats-of-formation vary between -57 and -77 Kcal/mole, with -70 ± 10 Kcal/mole being the best available estimate for $\text{AlN}_{(s)}$. However, since AlN is a minor constituent in a fluorine or an oxygen atmosphere, the uncertainty in its properties is relatively insignificant in this study.

In general, data for the beryllium compounds are not as well known. Both low and high temperature heat capacity data are needed on $\text{Be}(\text{OH})_2$, BeF_2 , BeCl_2 , BeF , and BeCl , but molecular constants are available. The mixed halide BeFCl has been proposed but not verified experimentally. Data on beryllium oxide are somewhat more complete, including the high temperature vapor phase. Gaseous polymers containing two to six BeO molecules have been identified by Chupka in the mass spectrograph.⁶⁶ Although this is of basic interest, the effect on rocket performance is not significant since the condensed phase is the predominant oxide species. Solid BeO is more volatile in the presence of water vapor, suggesting the formation of $\text{Be}(\text{OH})_2$. The properties of BeOH are estimated values.

The basic low and high temperature properties of the more significant magnesium compounds are fairly well defined. Some refinements would be useful in the molecular constants of the halides, and direct evidence has not been found for the existence of the mixed halides. Since magnesium oxide is an extremely high-melting compound, the gaseous oxide species are relatively unimportant in this study.

Experimental low temperature data are available on all important stable lithium compounds except LiCl . Some data are also available on these species in the high temperature range although the number of investigators has not been plentiful. Probably the most questionable data are those near the transition temperatures of LiF , LiCl , and Li_2O . The polymeric gaseous halides $(\text{LiF})_2$, $(\text{LiF})_3$, $(\text{LiF})_4$, $(\text{LiCl})_2$, and $(\text{LiCl})_3$ have also been reported by Chupka.⁶⁷ The thermodynamic properties of these molecules need to be further refined, particularly since the lithium halides are gases at normal

rocket combustion temperatures.

The products of combustion of boron have been studied more extensively than those of either lithium, beryllium, aluminum or magnesium. However, the problem is a more complex one, particularly in the case of the boron oxides. B_2O_3 , the principal stable oxide, melts and vaporizes at much lower temperatures than Al_2O_3 , BeO , or MgO . This means that the vapor species play a more dominant role in the combustion of a boron-oxygen system. Also, the possible number of high temperature boron species exceeds that of lithium because of the greater valence and coordination number of boron. Probably the most controversial questions concerning the thermodynamic properties of B_2O_3 arise from the inconsistency of the molecular constant data with the thermochemical data for that molecule. Also, the structure of the crystalline state has not been absolutely resolved. The most probable sources of error in the thermochemical data are the heat capacity of the liquid and the heat-of-fusion.⁶⁸ The gaseous species H_3BO_3 and HBO_2 are significant at low and high temperatures, respectively. In fact, HBO_2 is the predominant boron species in the B-O-H system at temperatures above 2000°K. Although the heat-of-formation of HBO_2 has been questionable for some time, recent data have fairly well established a maximum ΔH_f° of -140.8 Kcal/mole.^{69,70} Even more recent studies by White indicate the ΔH_f° of HBO_2 to be -134.5 Kcal/mole at 298°K. The data for the halides BCl , BCl_3 , BF , and BF_3 are considered reliable. The existence of the subhalide BCl_2 has been suggested by the existence of the dimer B_2Cl_4 . Data for BF_2 have also been estimated similarly to those for BCl_2 , AlF_2 , and $AlCl_2$. Direct evidence is available for the existence of BF_2Cl , $BFCl_2$, and $BFCl$, although the data on these

molecules need refinement.^{72,73} The oxyhalides BOF and BOC1 are hypothetical molecules whose properties have been estimated assuming a linear molecule.

In general, accurate heat-of-formation data are needed most for conducting theoretical performance calculations. However, another area of almost equal importance is that of high temperature properties. Both qualitative and quantitative data are needed. Experimental measurements of high temperature heat capacities and heats-of-transition are needed for solids and liquids. Although these studies may require new experimental techniques and equipment, they will undoubtedly refine the data now available. More detailed discussions of the thermodynamic properties of the reactants and products considered in this study may be found in the original literature citations listed in the footnotes and the bibliography.

In Table II, the enthalpy data at 298°K are the standard heats-of-formation of the various species, i.e. the heats-of-reaction for the formation of the species from their elements existing in their standard states. At higher temperatures, the enthalpy consists of the standard heat-of-formation at 298°K plus the heat content above that temperature. Of course, the entropy data are absolute values at a pressure of 1 atmosphere. In the two heat capacity equations, T is expressed as degrees Kelvin times 10^{-3} .

TABLE II

STANDARD VALUES OF ENTHALPY AND ENTROPY FOR PRODUCTS OF COMBUSTION

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
H	+52.089	27.393	298	+65.511	38.862	3000
H ₂	0	31.211	298	+21.208	48.470	3000
H ₂ O	-57.798	45.106	298	-27.598	68.419	3000
HCl	-22.063	44.645	298	-0.198	62.364	3000
HF	-64.2	41.526	298	-43.121	58.709	3000
C(s)	0	1.361	298	+14.78	12.30	3000
C(g)	+170.89	37.762	298	+184.44	49.29	3000
CO	-26.416	47.214	298	-4.059	65.370	3000
CO ₂	-94.052	51.070	298	-57.520	79.841	3000
O	+59.55	38.469	298	+73.071	50.095	3000
O ₂	0	49.011	298	+23.455	67.980	3000
OH	+9.33	43.888	298	+30.786	61.376	3000
N	+113.00	36.61	298	+126.437	48.089	3000
N ₂	0	45.763	298	+22.160	63.756	3000
NO	+21.60	50.339	298	+44.324	68.854	3000
F	+18.903	37.917	298	+33.641	49.791	3000
F ₂	0	48.477	298	+24.192	68.436	3000
Cl	+28.942	39.457	298	+44.066	51.623	3000
Cl ₂	0	53.291	298	+24.416	73.761	3000
CF	+83.0	50.889	298	+106.45	70.122	3000
CF ₂	-18.0	58.254	298	+17.405	86.974	3000
CF ₃	-120.0	62.352	298	-70.142	102.163	3000
CF ₄	-218.0	62.635	298	-153.43	113.842	3000
CH	+143.0	42.34	298	+164.9	60.03	3000
CH ₂	+66.0	44.92	298	+97.0	68.88	3000
CH ₃	-17.89	44.50	298			
C ₂ H ₂	+54.2	48.00	298	+101.0	84.08	3000
CHF ₃	-162.6	62.04	298	-101.5	109.16	3000
CH ₂ F ₂	-105.5	58.92	298	-47.56	102.26	3000
NH	+77.0	43.30	298	+98.77	60.93	3000
NH ₂	+41.0	47.96	298	+71.19	71.348	3000
NH ₃	-11.04	46.034	298			
CN	+94.0	48.41	298	+117.24	66.98	3000
C ₂ N ₂	+73.8	57.91	298	+124.95	98.77	3000
HCN	+31.20	48.21	298	+66.79	75.86	3000
COF ₂	-150.5	61.82	298	-101.4	100.56	3000
Al(1)				+21.330	25.217	3000
Al(g)	+77.5	39.31	298	+90.88	50.842	3000
AlH	+61.4	44.84	298	+84.79	63.842	3000
AlCl	-11.5	54.43	298	+12.90	75.120	3000
AlCl ₂	-76.0	63.025	298	-36.671	96.914	3000
AlCl ₃	-140.4	75.73	298	-87.61	120.086	3000
AlF	-59.2	51.450	298	-35.19	71.552	3000
AlF ₂	-172.0	57.330	298	-132.874	90.768	3000

TABLE II CONTINUED

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
AlF ₃	-283.0	66.11	298	-231.012	109.17	3000
AlFCl ₂	-185.0	72.430	298	-132.523	116.643	3000
AlF ₂ Cl	-228.0	70.885	298	-176.619	114.976	3000
AlFCl	-121.0	61.962	298	-82.035	95.341	3000
AlOCl	-56.0	60.580	298	-14.818	94.216	3000
AlOF	-100.0	57.317	298	-61.677	90.055	3000
AlO	+16.8	52.16	298	+40.61	71.897	3000
Al ₂ O	-39.4	61.200	298	-4.160	89.710	3000
Al ₂ O ₃ (s)	-400.2	12.172	298	-339.3	69.736	2313
Al ₂ O ₃ (l)				-313.3	80.977	2313
Al ₂ O ₃ (g)	-105.0	63.765	298	-50.56	108.54	3000
AlN(g)	+104.0	51.707	298	+128.26	71.776	3000
AlF ₃ (g)	-355.7	15.89	298	-346.19	34.907	727
AlN ₃ (s)	-70.0	5.0	298	-63.896	15.738	900
B(s)				+9.880	11.15	2000
B(l)				+22.630	16.47	3000
B(g)	+135.2	36.649	298	+148.62	48.121	3000
B ₂ (g)	+204.0	48.231	298	+227.607	67.850	3000
BH	+117	41.047	298	+139.63	59.314	3000
BN(s)	-60.3	3.37	298	-52.239	15.10	1200
BN(g)	+155.0	50.712	298	+178.169	69.616	3000
BCl	+46.23	50.944	298	+70.233	70.881	3000
BCl ₂	-24.0	59.134	298	-14.807	91.104	3000
BCl ₃	-97.1	69.320	298	-45.342	111.940	3000
BF	-42.87	47.892	298	-19.583	66.935	3000
BF ₂	-154.0	53.235	298	-116.99	82.547	3000
BF ₃	-270.0	60.71	298	-220.31	100.32	3000
BFC1	-89.0	57.376	298	-51.130	87.936	3000
BF ₂ Cl	-210.0	65.688	298	-159.597	106.312	3000
BFC1 ₂	-154.0	68.784	298	-102.859	110.488	3000
BOCl	-62.0	56.706	298	-24.164	87.50	3000
BOF	-118.0	54.342	298	-80.505	84.674	3000
BO	+16.0	48.609	298	+38.015	67.026	3000
B ₂ O ₂	-105.14	57.33	298	-53.58	98.44	3000
HBO ₂	-140.8	57.660	298	-94.269	93.760	3000
H ₂ BO ₃	-238.6	68.82	298	-158.40	131.11	3000
B ₂ O ₃ (g)	-206.57	64.39	298	-145.11	111.70	3000
B ₂ O ₃ (l)	-281.65	49.38	1000			
B ₂ O ₃ (s)	-300.98	18.55	298	-294.36	33.15	600
(HBO ₂) ₃	-531.26	85.12	298	-371.76	208.82	3000
Ba(s)	0	2.28	298			
Ba(l)				+10.715	13.684	1556
Ba(g)	+77.9	32.55	298	+91.338	44.02	3000
BeH	+76.0	42.19	298	+98.744	60.782	3000
BeCl	+13.0	51.993	298	+37.030	71.920	3000
BeCl ₂	-84.0	57.87	298	-44.762	89.828	3000
BeF	-16.5	49.151	298	+6.963	68.399	3000
BeF ₂ (g)	-192.10	52.256	298	-154.65	82.294	3000

TABLE II CONTINUED

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
BeF ₂ (l)				-222.93	34.468	1076
BeF ₂ (s)	-241.7	9.000	298			
BeFCl	-134.0	55.960	298	-95.440	87.630	3000
BeO(s)	-143.1	3.370	298	-111.243	28.754	2823
BeO(l)				-94.243	34.776	2823
BeO(g)	+30.1	47.208	298	+53.282	66.140	3000
(BeO) ₂				-67.026	85.570	2242
(BeO) ₃				-197.539	115.771	2242
(BeO) ₄				-301.052	146.668	2242
(BeO) ₅				-404.565	173.868	2242
(BeO) ₆				-514.078	196.907	2242
Be(OH) ₂	-159.72	54.964	298	-134.463	87.365	1500
BeOH	-28.0	54.202	298	+3.787	79.727	3000
Be(OH) ₂ (s)	-216.1	13.30	298			
Be ₃ N ₂ (s)	-121.47	34.67	800			
Li(g)	+38.430	33.140	298	+51.965	44.65	3000
Li(l)				+9.684	19.78	1600
Li ₂	+50.47	47.021	298	+75.421	67.998	3000
LiH	+32.0	40.78	298	+55.53	59.97	3000
LiCl	-49.0	50.834	298	-24.623	71.191	3000
(LiCl) ₂				-88.504	111.891	3000
LiCl(l)	-80.34	38.074	1200			
LiF	-77.60	47.754	298	-53.33	67.674	3000
(LiF) ₂				-176.21	96.463	3000
(LiF) ₃				-260.66	155.421	3000
LiO	+13.8	46.65	298	+36.99	65.60	3000
Li ₂ O(s)	-142.4	9.06	298			
Li ₂ O(l)				-68.68	63.61	3000
Li ₂ O(g)	-35.80	55.820	298	-1.19	83.430	3000
LiO ₂	-63.0	54.370	298	-25.95	83.871	3000
LiOH	-53.8	53.366	298	-22.238	77.923	3000
(LiOH) ₂				-87.76	118.619	3000
LiF(s)	-146.3	8.57	298			
LiF(l)				-115.7	39.54	2000
Li ₃ N(s)	-47.5	8.90	298			
Mg(l)				+7.01	18.29	1000
Mg(g)	+35.6	35.51	298	+49.038	46.97	3000
MgH	+41	46.11	298	+64.573	65.443	3000
MgCl	+2.0	55.34	298	+28.646	76.444	3000
MgCl ₂ (g)	-103.7	61.65	298	-64.83	94.324	3000
MgCl ₂ (l)				-129.76	54.59	1000
MgF	-41.0	52.814	298	-16.862	72.948	3000
MgF ₂ (g)	-169.7	55.92	298	-130.66	88.344	3000
MgF ₂ (l)				-215.91	58.32	2000
MgFCl	-137.0	60.054	298	-97.822	93.607	3000
MgO(g)	+13.9	50.944	298	+37.991	70.992	3000
MgO(l)				-89.402	40.234	3073
MgO(s)	-107.90	34.214	3073			
MgCl ₂ (s)	-142.06	42.00	900			

TABLE II CONTINUED

Reaction Product	ΔH_f Kcal/mole	S cal/mole/°K	Temp. °K	H Kcal/mole	S cal/mole/°K	Temp. °K
MgF ₂ (s)	-241.0	42.81	1500			
MgOH	-56.0	56.981	298	-23.014	83.126	3000
Mg(OH) ₂ (s)	-221.0	15.09	298			
Mg ₃ N ₂ (s)	-110.3	21.0	298	-95.99	48.098	823
ClF	-13.423	52.062	298	-0.8510	65.808	1500
ClO	+43.00	54.379	298	+53.501	68.217	1500

TABLE III

SUMMARY OF CONSTANTS OF THE HEAT CAPACITY EQUATION
 $C_p = a + bT + cT^2 + dT^3 + eT^4$ FOR PRODUCTS OF COMBUSTION

Reaction Product	Temp. Range °K	a	b	c	d	e
H	298-1200	4.6491	2.1104	-4.9036	4.7721	-1.6529
H ₂	298-1200	4.9782	12.6667	-28.6774	27.5445	-9.2560
H ₂ O	298-1200	7.7840	-0.4000	4.6918	-2.7618	0.5388
HCl	298-1200	5.7282	7.8535	-18.3714	18.8757	-6.6140
HF	298-1200	5.3188	11.0072	-25.9848	25.7227	-8.8189
C(s)	298-1200	-0.8755	11.1421	-3.1995	-4.4184	2.4909
C(g)	298-1200	5.5345	-3.5997	8.1446	-7.7652	2.6446
CO	298-1200	6.5135	2.3674	-5.4030	8.1190	-3.6364
CO ₂	298-1200	4.3090	20.6041	-20.9840	11.8419	-2.7832
O	298-1200	5.5202	-1.1625	0.2062	1.0710	-0.6299
O ₂	298-1200	8.1634	-10.0674	28.6774	-27.5958	9.1338
OH	298-1200	7.2173	0.3874	-3.7090	5.6460	-2.2047
N	298-1200	4.9556	0.0600	-0.0889	0.0410	0
N ₂	298-1200	7.2990	-2.2393	4.0750	-0.6623	-0.6229
NO	298-1200	8.0151	-6.7019	15.9410	-12.5923	3.4646
F	298-1200	6.8092	-8.0466	16.0915	-14.8332	5.0394
F ₂	298-1200	5.0585	12.5570	-18.0551	12.6196	-3.4646
Cl	298-1200	1.5072	23.2522	-49.2232	44.3739	-14.5456
Cl ₂	298-1200	5.1523	17.0693	-31.3058	26.3340	-8.2644
CF	298-1200	6.7824	-0.3563	8.2324	-9.1886	3.0680
CF ₂	298-1200	7.1238	10.4083	-2.9395	-3.6248	1.9745
CF ₃	298-1200	1.7148	50.8439	-61.7657	36.4601	-8.5419
CF ₄	298-1200	0.6148	66.6450	-77.7637	44.3853	-9.9271
CH	298-1200	7.2683	-1.8710	3.1512	-1.0671	0.02430
CH ₂	298-1200	8.0892	-2.6220	9.9827	-6.3896	1.3184
CH ₄	298-1200	7.3974	-6.1618	43.8496	-39.3788	11.4581
C ₂ H ₂	298-1200	2.2834	41.8264	-59.7199	43.7790	-12.2479
CHF ₃	298-1200	-0.3747	59.4746	-69.6683	43.2455	-10.9599
CH ₂ F ₂	298-1200	3.7552	21.6690	5.1725	-17.4742	6.8712
NH	298-1200	7.0346	-0.2160	-0.6454	2.3496	-1.0510
NH ₂	298-1200	8.1021	-2.5106	9.3232	-6.4932	1.6039
NH ₃	298-1200	7.1234	2.3491	9.7882	-7.5632	1.7072
CN	298-1200	7.6062	-5.1455	12.8420	-10.0281	2.7218
C ₂ N	298-1200	7.5571	29.6794	-39.0639	28.2055	-8.1166
HCN	298-1200	4.6914	18.4680	-22.2652	15.6556	-4.3682
COF ₂	298-1200	2.6503	39.7213	-42.3295	22.5746	-4.8420
Al(s)	298-1200	3.9677	7.9856	-20.0784	20.3835	7.2441
Al(l)	900-6000	7.0	0	0	0	0
AlH	298-1200	7.7836	-7.6791	21.6722	-19.2239	5.7959
AlCl	298-1200	6.4388	9.9343	-15.7794	11.5580	-3.1835
AlCl ₂	298-1200	8.2309	25.9687	-41.3807	30.1295	-8.2564
AlCl ₃	298-1200	10.5301	35.6821	-56.1667	40.5592	-11.0510

TABLE III CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
AlF	298-1200	5.1754	12.1638	-16.5747	10.8250	-2.7339
AlF ₂	298-1200	4.9599	34.0210	-49.6949	34.0750	-8.9490
AlF ₃	298-1200	5.7138	44.9180	-61.7929	40.4308	-10.2369
AlFCl ₂	298-1200	6.7952	46.2482	-69.0741	48.0722	-12.7522
AlF ₂ Cl	298-1200	6.8416	43.4470	-62.1709	41.4930	-10.8748
AlFCl	298-1200	7.1218	26.3110	-38.1612	26.0522	-6.8226
AlOCl	298-1200	8.3706	19.4158	-25.4114	16.0854	-3.9854
AlOF	298-1200	5.9524	25.5204	-32.2289	19.7106	-4.7327
AlO	298-1200	4.9828	11.9091	-16.4703	11.3880	-3.1496
Al ₂ O	298-1200	5.4563	22.9840	-27.7457	16.2804	-3.7667
Al ₂ O ₃ (s)	298-1200	-6.5714	134.3794	-203.2832	144.0387	-38.7424
Al ₂ O ₃ (l)	2100-6000	31.15	2.0	0	0	0
AlN(g)	298-1200	7.7923	41.8087	-57.9975	38.2374	-9.7448
AlN(s)	298-900	5.8327	11.4582	-17.5701	12.4443	-3.3414
AlF ₃ (s)	298-727	5.47	7.80	0	0	0
AlF ₃ (l)	727-2000	2.580	86.775	-157.717	145.5	-48.5
B(1)	2100-6000	20.93	1.50	0	0	0
B(g)	298-1200	7.5	0	0	0	0
B ₂ (g)	298-1200	3.4917	9.8630	-23.0913	22.6147	-7.8740
BH	298-1200	5.8345	5.7108	-2.4451	-1.7599	1.2598
BN(s)	298-1200	7.4053	-3.2771	7.1383	-4.0601	0.6299
BN(g)	298-1200	1.5198	27.8125	-26.4121	14.4284	-3.6331
BCl	298-1200	7.1326	-3.5555	14.0143	-13.0869	4.1677
BCl ₂	298-1200	5.2489	11.3558	-14.8233	9.2787	-2.2540
BCl ₃	298-1200	4.9226	32.5208	-46.0491	30.9468	-8.0194
BF	298-1200	6.5126	43.1581	-60.1744	39.7437	-10.1276
BF ₂	298-1200	5.3144	8.3476	-11.7021	9.9308	-3.4646
BF ₃	298-1200	6.1558	7.3366	12.9662	-20.8438	7.8372
BFC1	298-1200	3.6440	39.0299	-42.9112	23.7218	-5.3543
BFC1 ₂	298-1200	3.0732	32.6145	-40.5830	24.7328	-5.9538
BOCl	298-1200	13.3393	-8.0392	47.1216	-51.4582	17.4848
BOF	298-1200	5.9286	40.4030	-52.1268	32.6017	-7.9951
BO	298-1200	6.1872	22.5827	-29.6029	19.9190	-5.3220
B ₂ O ₂	298-1200	7.7388	10.6700	-3.9988	-2.2705	1.5553
HBO ₂	298-1200	7.9062	-7.6457	19.9985	-17.5116	5.3543
H ₂ BO ₃	298-1200	10.1212	19.6261	-19.6396	11.6047	-3.0012
B ₂ O ₃ (s)	298-1200	4.7597	24.2014	-19.4200	8.2347	-1.4398
B ₂ O ₃ (l)	298-1200	0.1952	79.1232	-91.5570	55.9425	-13.7120
B ₂ O ₃ (g)	298-1200	5.4370	39.1950	-34.4995	15.0008	-2.5699
(HBO ₂) ₃	298-600	-52.30	488.83	-1190.0	1016.67	0
Be(s)	298-1700	-1.2880	161.8829	-189.244	111.294	-25.9599
Be(1)	1400-6000	4.13	2.4	0	0	0
Be(g)	298-2500	7.5	0	0	0	0
BeH	298-1200	4.97	0	0	0	0
		10.6340	-22.5709	47.4823	-38.7665	11.2880

TABLE III CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
BeCl	298-1200	5.2314	11.4345	-14.9863	9.4369	-2.3086
BeCl ₂	298-1200	5.1303	31.6832	-44.6868	29.9397	-7.7400
BeF	298-1200	6.1152	3.3155	0.9714	7.0498	1.1968
BeF ₂ (g)	298-1200	2.4903	31.1361	-34.9557	17.2050	-4.1859
BeF ₂ (l)	1000-6000	21.0	0	0	0	0
BeF ₂ (s)	298-1200	8.4	12.0	0	0	0
BeFCl	298-1200	5.8566	26.5295	-35.2020	22.7686	-5.7716
BeO(s)	298-1200	-5.6027	61.5775	-93.2205	58.0057	-18.8518
BeO(l)	2700-6000	14.5	0	0	0	0
BeO(g)	298-1200	7.0077	-2.8128	12.7681	12.5039	3.9368
Be(OH) ₂	298-1200	-0.6491	79.4228	-119.3368	86.4588	-23.7485
BeOH	298-1200	7.4132	-0.5027	14.1321	-14.6854	4.7205
BeO(s)	1200-3000	11.93	0.91	0	0	0
Be ₃ N ₂ (s)	298-800	7.32	30.8	0	0	0
Li(g)	298-1200	4.97	0	0	0	0
Li(l)	500-6000	6.87	0	0	0	0
Li ₂	298-1200	7.3496	6.8209	-10.6540	7.9135	-2.1993
LiH	298-1200	6.6048	-0.7687	10.0114	-10.8285	3.5662
LiCl	298-1200	5.6195	11.9363	-18.0048	12.6189	-3.3657
LiF	298-1200	5.2328	10.6854	-12.9571	7.5804	-1.7254
LiO	298-1200	6.9059	-1.8393	10.5388	-10.6287	3.3779
Li ₂ O(s)	298-1900	2.4011	51.2102	-62.7011	38.2906	-8.5721
Li ₂ O(l)	1500-6000	24.0	0	0	0	0
Li ₂ O(g)	298-1200	6.1995	9.1561	1.7129	-7.6438	3.1166
Li ₂ O ₂ (g)	298-1200	2.8280	29.2237	-33.5974	19.6045	-4.6172
LiOH	298-1200	8.3729	-6.3251	23.2359	-20.5663	6.1118
LiF(s)	298-1200	2.1602	43.3753	-72.9975	58.1838	-16.4581
LiF(l)	1000-6000	15.5	0	0	0	0
LiCl(l)	880-1200	17.0691	-1.52	0	0	0
Li ₃ N(s)	298-800	11.73	23.0	0	0	0
Mg(l)	900-6000	8.1	0	0	0	0
Mg(s)	298-2500	4.97	0	0	0	0
MgH ₂	298-1200	6.9688	-3.2669	14.7073	-14.4920	4.6051
MgCl	298-1200	6.5499	9.5397	-15.1524	11.1001	-3.0559
MgCl ₂ (g)	298-1200	8.1795	26.3921	-42.2976	30.9229	-3.4994
MgCl ₂ (l)	900-6000	22.1	0	0	0	0
MgF	298-1200	5.4028	12.1908	-17.5182	11.8730	-3.0802
MgF ₂ (g)	298-1200	4.1208	38.3454	-57.5026	40.1424	-10.6744
MgF ₂ (l)	1400-6000	22.6	0	0	0	0
MgFCl	298-1200	5.8100	33.7002	-52.0243	37.0813	-10.0122
MgO(g)	298-1200	5.2592	12.0747	-16.6978	11.0012	-2.7946
MgO(l)	2900-6000	14.5	0	0	0	0
MgOH	298-1200	5.8757	13.4434	-13.5188	7.2214	-1.5067
MgO(s)	300-3200	9.965	1.305	0	0	0

TABLE III CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
$MgF_2(s)$	400-2000	16.47	2.76	0	0	0
$Mg_3N_2(s)$	298-823	20.77	11.20	0	0	0
$Mg_3N_2(s)$	823-1061	20.07	10.66	0	0	0
$Mg_3N_2(s)$	1061-2000	28.5	0	0	0	0
ClF	298-1200	5.5350	10.5214	-13.6836	8.2632	-1.8898
ClO	298-1200	-2.0832	6.0494	3.7874	-2.3555	0.5893

TABLE IV

SUMMARY OF CONSTANTS OF THE HEAT CAPACITY EQUATION
 $C_p = a + bT^{-1} + cT^{-2} + dT^{-3} + eT^{-4}$ FOR PRODUCTS OF COMBUSTION

Reaction Product	Temp. Range °K	a	b	c	d	e
H	1200-6000	4.9680	0	0	0	0
H ₂	1200-6000	13.1615	-27.4278	67.2718	-84.8607	40.7688
H ₂ O	1200-6000	13.7762	1.8181	-19.5586	21.5310	-7.7672
HF	1200-6000	10.2217	-7.2070	15.6488	-22.0974	11.6068
HF	1200-6000	12.3357	-25.0605	67.8036	-91.7611	45.9920
C(s)	1200-6000	8.9014	-14.7665	31.8293	-33.9478	13.2068
C(g)	1200-6000	5.7187	0.3176	-13.1090	27.1718	-16.0
CO	1200-6000	8.9548	3.1902	-17.8004	28.4934	-16.0
CO ₂	1200-6000	17.0619	-10.1588	-17.6949	-18.8447	7.2457
O	1200-6000	6.7126	-13.5630	39.3302	-49.8513	23.2136
O ₂	1200-6000	11.0432	-3.3193	-9.4192	22.2363	-12.6224
OH	1200-6000	11.11.6	-12.8166	27.9832	-36.0147	17.8456
N	1200-6000	11.2577	-52.8970	162.330	-214.4616	102.7204
N ₂	1200-6000	9.4233	-1.7978	0.1459	0.8427	1.0156
NO	1200-6000	10.1998	-8.4006	23.0720	-31.8463	15.8143
F	1200-6000	4.9810	0.3996	-1.3628	2.3392	-1.3058
F ₂	1200-6000	8.8708	0.8054	-3.4224	5.1525	-2.9017
Cl	1200-6000	5.1251	-1.7062	7.2114	-10.6191	5.6584
Cl ₂	1200-6000	11.0049	-12.3026	33.9264	-43.7925	21.0372
CF	1200-6000	9.7813	-3.6223	7.1708	-8.0166	3.2911
CF ₂	1200-6000	13.9133	-0.03111	-1.0264	-0.1186	0.2110
CF ₃	1200-6000	23.5138	-20.5833	52.6576	-66.2369	30.0422
CF ₄	1200-6000	30.2094	-21.8359	47.4496	-52.9712	21.6034
CH	1200-6000	10.5378	-8.2322	16.2034	-20.1049	9.2827
CH ₂	1200-6000	13.8698	0.5278	-9.6784	7.0023	-1.3080
C ₂ H ₂	1200-6000	21.0765	-2.7760	2.0961	-17.1159	13.3333
CH ₃	1200-6000	25.8030	0.3565	-8.0184	4.2406	-0.6329
CH ₃ F	1200-6000	25.7758	0.5723	-12.1526	6.1841	-0.2954
NH	1200-6000	10.5927	-8.4438	15.7380	-19.0571	8.8608
NH ₂	1200-6000	13.8508	0.8784	-13.6628	12.3590	-3.3755
CN	1200-6000	9.4034	25.5485	-119.9354	177.2701	-86.6245
C ₂ N ₂	1200-6000	21.3002	-4.0233	8.6897	-15.9300	8.4388
HCN	1200-6000	18.0749	-15.9472	31.9731	-39.9297	18.4810
COF ₂	1200-6000	19.8930	-0.2882	-1.4691	-1.6824	1.3924
Al(g)	1200-6000	6.7710	-16.8320	56.1522	-79.2737	40.0435
AlH	1200-6000	11.1719	-11.7417	27.5952	-32.2290	13.8397
AlCl	1200-6000	10.4069	-7.7297	18.7755	-21.3683	9.0717
AlCl ₂	1200-6000	14.9053	-0.01523	-0.1658	-0.07478	0.04219
AlCl ₃	1200-6000	19.8693	0.01952	-0.3761	0.04007	0
AlF	1200-6000	5.1754	12.1638	-16.5747	10.8250	-2.7339
AlF ₂	1200-6000	14.9017	0.0238	-0.6166	0.1412	-0.042

TABLE IV CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
AlF ₃	1200-6000	19.8763	-0.0514	-0.7156	-0.2812	0.2110
AlFCl ₂	1200-6000	19.8743	-0.0300	-0.4986	-0.1797	0.1266
AlF ₂ Cl	1200-6000	19.8738	-0.0247	-0.6365	-0.1499	0.1266
AlFC1	1200-6000	14.9100	-0.06719	-0.1884	-0.3579	0.2110
AlOC1	1200-6000	14.9088	-0.05508	-0.3275	-0.3052	0.2110
AlOF	1200-6000	14.9030	0.0087	-0.7949	0.0626	0.0422
AlO	1200-6000	8.6384	3.3156	-12.9668	19.9806	-11.0265
Al ₂ O	1200-6000	13.9092	0.01136	-0.8344	0.07978	0.04219
Al ₂ O ₃ (s)	1200-2500	55.0332	-84.0657	105.1027	-47.4432	0
Al ₂ O ₂	1200-6000	20.8688	-0.03878	-0.6914	-0.2064	0.1688
AlN(g)	1200-6000	8.9423	0.001028	-0.1281	0.008015	0
AlN(s)	900-3000	14.699	0	-1.789	0	0
B(s)	1000-2400	10.3983	-7.0962	-4.2064	15.8978	-9.3332
B(g)	1200-6000	5.3886	-4.5609	16.9404	-26.4531	14.5085
B ₂ (g)	1200-6000	9.1384	-1.4373	3.0706	-3.0243	0.7254
BH(g)	1200-6000	8.7146	2.4833	-11.2827	15.2569	-7.8346
BN(s)	1200-6000	18.0317	-37.9094	95.3357	-11.5386	47.6000
BN(g)	1200-6000	9.9021	-5.0205	11.3351	-13.5906	5.8650
BC1(g)	1200-6000	10.2413	-6.8557	16.4790	-18.9494	8.0591
BC1 ₂	1200-6000	14.9077	-0.0398	-0.5047	-0.1671	0.1266
BC1 ₃	1200-6000	19.8782	-0.0711	-0.5586	-0.3812	0.2532
BF	1200-6000	8.7610	1.9896	-8.2963	12.1788	-6.6739
BF ₂	1200-6000	14.9054	-0.0149	-1.6857	0.0081	0.2532
BF ₃	1200-6000	19.7823	0.9185	-5.3913	5.1252	-2.4664
BFC1	1200-6000	14.9062	-0.0224	-1.1104	-0.0553	0.1688
BF ₂ Cl	1200-6000	19.8719	-0.0004	-1.6333	0.0604	0.1688
BFC1 ₂	1200-6000	19.8794	-0.0826	-0.8952	-0.4174	0.3376
BOCl	1200-6000	14.9077	-0.0334	-1.4348	0.0375	0.2954
BOF	1200-6000	14.9050	-0.0029	-1.8188	0.2612	0.2532
BO	1200-6000	10.2272	-9.1175	25.9717	-36.2764	18.1357
E ₂ O ₂	1200-6000	20.8674	-0.0048	-3.1009	0.5032	0.4641
HEO ₂	1200-6000	4.7597	24.2014	19.4200	8.2347	-1.4398
H ₂ BO ₃	1200-6000	37.6781	1.1163	-20.0353	14.5691	-3.2911
B ₂ O ₃ (g)	1200-6000	25.8298	0.0601	-4.6868	0.9570	0.4219
B ₂ O ₃ (l)	600-6000	30.5	0	0	0	0
B ₂ O ₃ (gl)	600-6000	30.5	0	0	0	0
(HBO ₂) ₃	1200-6000	67.4341	1.7731	-28.7114	22.4454	-6.2447
Be(g)	2500-6000	21.9304	-148.4244	435.4418	-428.4375	5.00
BeH	1200-6000	10.9483	-10.5468	24.1330	-28.6829	12.4894
BeCl	1200-6000	10.2809	-7.0561	16.9462	-19.4619	8.2700
BeCl ₂	1200-6000	14.9066	-0.0294	-0.5268	-0.1476	0.1266
BeF	1200-6000	10.5587	-10.5803	28.9426	-36.5533	16.6245
BeF ₂ (g)	1200-6000	14.9061	-0.0226	-1.3434	-0.0556	0.2110
BeFC1(g)	1200-6000	14.9098	-0.0631	-0.6087	-0.3033	0.2532
BeO(g)	1200-6000	9.9108	-5.0763	11.5275	-13.7951	5.9494

TABLE IV CONTINUED

Reaction Product	Temp. Range °K	a	b	c	d	e
(BeO) ₂	1000-6000	19.981	0	-2.207	0	0
(BeO) ₃	1000-6000	31.957	0	-3.278	0	0
(BeO) ₄	1000-6000	43.870	0	-3.083	0	0
(BeO) ₅	1000-6000	55.846	0	-4.154	0	0
(BeO) ₆	1000-6000	67.760	0	-3.959	0	0
Be(OH) ₂	1200-6000	26.7677	0.8694	-14.3231	12.1060	-3.2489
BeOH	1200-6000	13.8695	0.6035	-9.5250	8.8324	-2.7004
Be(OH) ₂ (s)	298-6000	35.211	0	-1.903	0	0
Be ₃ N ₂ (s)	800-2600	36.753	0	-3.067	0	0
Li ₂	1200-6000	13.6444	-24.7845	60.3401	-68.3563	28.9873
LiH	1200-6000	11.8739	-15.4597	36.9991	-42.6350	18.1856
LiCl	1200-6000	8.9450	-0.0290	-0.0397	-0.1542	0.0844
(LiCl) ₂	1000-6000	19.969	0	-1.969	0	0
LiF(g)	1200-6000	10.8294	-9.9162	23.8040	-27.1839	11.5190
(LiF) ₂	1000-6000	19.969	0	-1.969	0	0
(LiF) ₃	1000-6000	31.788	0	-1.788	0	0
LiO	1200-6000	8.9422	0.0040	-0.7480	0.0737	0.0844
Li ₂ O(g)	1200-6000	13.9102	0.0039	-1.7148	0.1367	0.2110
LiO ₂ (g)	1200-6000	14.9121	-0.0823	-1.5936	-0.2421	0.4641
LiOH	1200-6000	13.8676	0.6242	-9.9390	8.8958	-2.6160
(LiOH) ₂	1000-6000	31.735	0	-2.735	0	0
LiCl(1)	1200-6000	15.2	0	0	0	0
Mg(g)	2500-6000	25.8927	-188.3282	566.1888	-566.0000	0
MgH	1200-6000	11.8517	-15.3516	36.6664	-42.3675	18.1013
MgCl	1200-6000	10.5230	-8.3132	20.1329	-22.8263	9.6624
MgCl ₂ (g)	1200-6000	14.9119	-0.0885	0.1132	-0.4842	0.2532
MgF	1200-6000	10.2757	-7.0273	16.9432	-19.3802	8.2278
MgF ₂ (g)	1200-6000	14.9101	-0.0675	-0.2527	-0.3625	0.2110
MgFCl	1200-6000	14.9049	-0.0114	-0.3259	-0.0553	0.0422
MgO(g)	1200-6000	10.3480	-7.4032	17.8101	-20.3834	8.6498
MgOH	1200-6000	13.8733	0.5641	-8.8582	8.6828	-2.7426
MgCl ₂ (s)	298-1100	19.917	0	-0.258	0	0
Mg(OH) ₂ (s)	298-6000	39.391	-13.946	2.293	0	0
ClF	1200-6000	20.7734	-97.8828	295.5712	-385.2596	182.2271
ClO	1200-6000	135.5942	-750.9014	1852.353	-2111.363	899.1561
Li(g)	1200-6000	15.6816	-81.3779	231.0344	-287.9056	132.0276

CHAPTER VI

RESULTS

A. Summary of the Results

The performance of 100 prototype propellant systems has been evaluated, with each of the ten selected fuels being considered in combination with each of the ten oxidizers. All calculations were made at a combustion pressure of 1000 psi expanding to exhaust pressures of 14.696 psi (1 atmosphere), 2.0 psi, and 0.2 psi. The latter exhaust conditions were chosen to simulate high altitude operation where large nozzle area ratios are desirable. The temperature, enthalpy, entropy, heat capacity, and molecular composition of the combustion products were determined for the chamber and each exhaust condition. Then, assuming shifting chemical equilibrium accompanied by complete phase equilibrium, the following performance parameters were evaluated:

- (1) Specific impulse.
- (2) Specific heat capacity ratio.
- (3) Volumetric specific impulse.
- (4) Thrust coefficient.
- (5) Nozzle area ratio.

Also, the following parameters were evaluated for the condition of complete frozen equilibrium:

- (1) Specific impulse.
- (2) Characteristic exhaust velocity.
- (3) Thrust coefficient.
- (4) Nozzle area ratio.

Since the prime purpose of this study was to evaluate the chemical performance of prototype propellant systems, the shifting specific impulse has been considered the most important single parameter. As shown earlier, this represents the maximum energy attainable from a chemical propulsion

system. This, and some other significant parameters, have been plotted in a series of three graphs for each propellant system. The first presents both the shifting and frozen specific impulse as a function of the propellant composition for each of the three exhaust pressures. The second presents the corresponding exhaust temperatures at each exhaust pressure. Finally, the third graph presents the chamber temperature, the chamber molecular weight, and the characteristic exhaust velocity as a function of the propellant composition. These graphs constitute Appendix C. Unfortunately, the volume of output information from the computer was much too large to be incorporated in its entirety into this report. Two pages of output were obtained for each chemical formulation considered. However, since the complete output contains additional data which was not plotted, including the molecular composition, the complete output is presented for one fuel-to-oxidizer ratio of each propellant system. This constitutes Appendix D. The molecular composition is of particular importance since it indicates the relative concentrations of the various combustion products as well as those which were considered in making the calculations. It should be pointed out that 298°K constitutes a minimum temperature limit in the calculations. During the frozen flow expansion to 0.2 psi, the temperature dropped to this point in a few instances. In these cases, the true frozen exhaust temperature lies somewhere below 298°K. There is no maximum temperature limit to the calculations. A linear heat capacity is automatically assumed above the maximum temperature for which thermodynamic data are provided, if this temperature should be exceeded.

In addition to the compilation of data in Appendices C and D, the maximum shifting specific impulses of the various systems are summarized in six tables within this chapter. Each of the various oxidizers is listed, in order of its performance, with each of the fuels in Tables V, VI, and VII. These are for exhaust pressures of 14.7 psi, 2.0 psi, and 0.2 psi respectively. Conversely, in Tables VIII, IX, and X, the various fuels are tabulated in order of their performance with each oxidizer. The combustion temperature at the point of maximum specific impulse is also listed. These tables provide a concise presentation of the relative energy available from the various systems. Following these tables is a brief discussion of the more significant findings of this study. The discussion is subdivided by fuels.

Table V

Summary of Maximum Shifting Specific Impulse

pc = 1000 psi
 Pe = 14.696 psi

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H ₂	OF ₂	85.5	411	3591
H ₂	F ₂	89	410	3964
H ₂	O ₂	78	391	2769
H ₂	NF ₃	93	351	3876
H ₂	NO ₂ ClO ₄	83	349	2713
H ₂	ClO ₃ F	84	344	2744
H ₂	N ₂ O ₄	84	342	2660
H ₂	H ₂ O ₂	88	322	2404
H ₂	ClF ₃	92	318	3403
H ₂	NH ₄ ClO ₄	91	287	2448
N ₂ H ₄	F ₂	69	363	4688
N ₂ H ₄	OF ₂	60	345	4037
N ₂ H ₄	NF ₃	73	322	4242
N ₂ H ₄	O ₂	48	313	3409
N ₂ H ₄	NO ₂ ClO ₄	56	295	3363
N ₂ H ₄	ClO ₃ F	59.5	295	3466
N ₂ H ₄	ClF ₃	73	293	3882
N ₂ H ₄	N ₂ O ₄	57	291	3257
N ₂ H ₄	H ₂ O ₂	67	286	2923
N ₂ H ₄	NH ₄ ClO ₄	73	265	2969
CH ₂	OF ₂	79	350	4650
CH ₂	F ₂	72.5	325	4382
CH ₂	O ₂	73	300	3683
CH ₂	NF ₃	78	287	3781
CH ₂	ClO ₃ F	81	280	3722
CH ₂	NO ₂ ClO ₄	79	278	3586
CH ₂	H ₂ O ₂	86.5	277	2999
CH ₂	N ₂ O ₄	80	276	3444
CH ₂	ClF ₃	77	257	3541
CH ₂	NH ₄ ClO ₄	90.5	252	3016

Table V Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
UDMH	OF ₂	72	351	4460
UDMH	F ₂	71	344	4342
UDMH	O ₂	63	310	3614
UDMH	NF ₃	76	309	3964
UDMH	ClO ₃ F	73	290	3666
UDMH	NO ₂ ClO ₄	70	289	3540
UDMH	N ₂ O ₄	72	286	3429
UDMH	H ₂ O ₂	81	283	3008
UDMH	ClF ₃	75	280	3794
UDMH	NH ₄ ClO ₄	85	259	3038
C ₄ N ₂	O ₂	49	302	4816
C ₄ N ₂	N ₂ O ₄	61	282	4224
C ₄ N ₂	H ₂ O ₂	75	280	3320
C ₄ N ₂	OF ₂	68	278	4061
C ₄ N ₂	NO ₂ ClO ₄	61	276	4272
C ₄ N ₂	NH ₄ ClO ₄	80	258	3333
C ₄ N ₂	ClO ₃ F	62	255	3708
C ₄ N ₂	F ₂	85	253	3891
C ₄ N ₂	NF ₃	85	232	3680
C ₄ N ₂	ClF ₃	87	203	3404
B ₅ H ₉	OF ₂	80	367	5169
B ₅ H ₉	F ₂	82	360	5101
B ₅ H ₉	O ₂	70	327	4518
B ₅ H ₉	NF ₃	87	326	4809
B ₅ H ₉	H ₂ O ₂	73	316	3400
B ₅ H ₉	ClO ₃ F	79	306	4447
B ₅ H ₉	N ₂ O ₄	77	306	4266
B ₅ H ₉	NO ₂ ClO ₄	78	302	4432
B ₅ H ₉	ClF ₃	88	290	4487
B ₅ H ₉	NH ₄ ClO ₄	82	285	3484
MgH ₂	F ₂	72	329	4963
MgH ₂	OF ₂	79	305	4516
MgH ₂	NF ₃	78	302	4620
MgH ₂	H ₂ O ₂	39	280	3073
MgH ₂	ClF ₃	78	275	4465
MgH ₂	O ₂	31	270	3076
MgH ₂	NH ₄ ClO ₄	50	266	3073
MgH ₂	N ₂ O ₄	40	265	3073
MgH ₂	NO ₂ ClO ₄	38	263	3114
MgH ₂	ClO ₃ F	46	260	3237

Table V Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
AlH ₃	F ₂	73.5	353	5317
AlH ₃	OF ₂	59	333	4406
AlH ₃	H ₂ O ₂	48	326	3923
AlH ₃	NF ₃	78	323	4956
AlH ₃	O ₂	42	318	4299
AlH ₃	N ₂ O ₄	52	308	4226
AlH ₃	NO ₂ ClO ₄	49	305	4175
AlH ₃	NH ₄ ClO ₄	58	302	3837
AlH ₃	ClO ₃ F	50	301	4029
AlH ₃	ClF ₃	77	291	4593
BeH ₂	F ₂	80.5	395	5331
BeH ₂	OF ₂	67	383	4347
BeH ₂	H ₂ O ₂	56.5	375	3574
BeH ₂	O ₂	54.5	371	4138
BeH ₂	NF ₃	81.5	359	4731
BeH ₂	N ₂ O ₄	50	351	3403
BeH ₂	NO ₂ ClO ₄	55	346	3394
BeH ₂	NH ₄ ClO ₄	62	340	3283
BeH ₂	ClO ₃ F	68	339	4173
BeH ₂	ClF ₃	81.5	329	4500
LiH	F ₂	82	363	4886
LiH	OF ₂	77	337	4093
LiH	NF ₃	85.5	319	4384
LiH	ClF ₃	84	293	4109
LiH	ClO ₃ F	76	272	3351
LiH	O ₂	66	263	3309
LiH	H ₂ O ₂	81	262	2711
LiH	NO ₂ ClO ₄	73	258	3292
LiH	NH ₄ ClO ₄	85	250	2754
LiH	N ₂ O ₄	74	250	3171

Table VI

Summary of Maximum Shifting Specific Impulse

pc = 1000 psi

pe = 2.0 psi

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H ₂	OF ₂	87	458	3756
H ₂	F ₂	92	457	4462
H ₂	O ₂	82	437	3182
H ₂	NF ₃	94.5	390	4212
H ₂	NO ₂ ClO ₄	86	389	3080
H ₂	ClO ₃ F	87	383	3273
H ₂	N ₂ O ₄	86	381	2891
H ₂	H ₂ O ₂	91	359	2740
H ₂	ClF ₃	93.5	352	3690
H ₂	NH ₄ ClO ₄	92.5	319	2660
N ₂ H ₄	F ₂	69	408	4688
N ₂ H ₄	OF ₂	63	392	4100
N ₂ H ₄	NF ₃	73	357	4242
N ₂ H ₄	O ₂	49	355	3425
N ₂ H ₄	NO ₂ ClO ₄	58	333	3375
N ₂ H ₄	ClO ₃ F	61	333	3478
N ₂ H ₄	N ₂ O ₄	59	329	3262
N ₂ H ₄	ClF ₃	73	325	3882
N ₂ H ₄	H ₂ O ₂	68	323	2916
N ₂ H ₄	NH ₄ ClO ₄	73	297	2969
CH ₂	OF ₂	79	393	4650
CH ₂	F ₂	72.5	371	4382
CH ₂	O ₂	73	344	3683
CH ₂	NF ₃	78	326	3781
CH ₂	ClO ₃ F	82	319	3734
CH ₂	NO ₂ ClO ₄	81	318	3603
CH ₂	N ₂ O ₄	82	316	3453
CH ₂	H ₂ O ₂	88	315	2979
CH ₂	ClF ₃	77	291	3541
CH ₂	NH ₄ ClO ₄	91	287	3001

Table VI Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
UDMH	OF ₂	75	400	4519
UDMH	F ₂	71	393	4342
UDMH	O ₂	65	354	3633
UDMH	NF ₃	76	348	3964
UDMH	ClO ₃ F	75	329	3686
UDMH	NO ₂ ClO ₄	73	328	3567
UDMH	N ₂ O ₄	74	325	3433
UDMH	H ₂ O ₂	81	321	3008
UDMH	ClF ₃	75	314	3794
UDMH	NH ₄ ClO ₄	86	293	3026
Cl ₄ N ₂	O ₂	52	342	4609
Cl ₄ N ₂	N ₂ O ₄	64	320	4127
Cl ₄ N ₂	OF ₂	68	320	4061
Cl ₄ N ₂	H ₂ O ₂	75	319	3320
Cl ₄ N ₂	NO ₂ ClO ₄	64	313	4168
Cl ₄ N ₂	NH ₄ ClO ₄	83	293	3264
Cl ₄ N ₂	F ₂	85	292	3891
Cl ₄ N ₂	ClO ₃ F	62	289	3708
Cl ₄ N ₂	NF ₃	85	269	3680
Cl ₄ N ₂	ClF ₃	87	235	3404
B ₅ H ₉	OF ₂	80	422	5169
B ₅ H ₉	F ₂	84	413	5165
B ₅ H ₉	O ₂	70	379	4518
B ₅ H ₉	NF ₃	88	374	4841
B ₅ H ₉	H ₂ O ₂	73	361	3400
B ₅ H ₉	ClO ₃ F	79	353	4447
B ₅ H ₉	N ₂ O ₄	79	353	4388
B ₅ H ₉	NO ₂ ClO ₄	79	350	4502
B ₅ H ₉	ClF ₃	88	333	4487
B ₅ H ₉	NH ₄ ClO ₄	73	330	3000
MgH ₂	F ₂	74	379	4991
MgH ₂	OF ₂	69	352	4404
MgH ₂	NF ₃	78	346	4620
MgH ₂	H ₂ O ₂	42	327	3073
MgH ₂	O ₂	33	316	3216
MgH ₂	ClF ₃	78	315	4465
MgH ₂	NH ₄ ClO ₄	50	311	3073
MgH ₂	N ₂ O ₄	44	310	3265
MgH ₂	NO ₂ ClO ₄	40	308	3124
MgH ₂	ClO ₃ F	49	305	3390

Table VI Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Second	Tc, °K
AlH ₃	F ₂	75	405	5346
AlH ₃	OF ₂	62	386	4447
AlH ₃	H ₂ O ₂	48	378	3923
AlH ₃	O ₂	44	371	4299
AlH ₃	NF ₃	81	370	5006
AlH ₃	N ₂ O ₄	52	358	4226
AlH ₃	NO ₂ ClO ₄	51	355	4252
AlH ₃	NH ₄ ClO ₄	58	350	3837
AlH ₃	ClO ₃ F	55	350	4204
AlH ₃	ClF ₃	80	333	4693
BeH ₂	F ₂	80.5	453	5331
BeH ₂	OF ₂	67	445	4347
BeH ₂	H ₂ O ₂	58	442	3708
BeH ₂	O ₂	53	436	4004
BeH ₂	NF ₃	81.5	413	4731
BeH ₂	N ₂ O ₄	50	411	3403
BeH ₂	NO ₂ ClO ₄	61	406	3866
BeH ₂	NH ₄ ClO ₄	62	398	3283
BeH ₂	ClO ₃ F	68	396	4173
BeH ₂	ClF ₃	81.5	378	4500
LiH	F ₂	82	410	4886
LiH	OF ₂	77	386	4093
LiH	NF ₃	85.5	360	4384
LiH	ClF ₃	84	330	4109
LiH	ClO ₃ F	76	312	3351
LiH	O ₂	66	306	3309
LiH	H ₂ O ₂	81	304	2711
LiH	NO ₂ ClO ₄	73	299	3292
LiH	NH ₄ ClO ₄	85	289	2754
LiH	N ₂ O ₄	74	290	3171

Table VII

Summary of Maximum Shifting Specific Impulse
 $p_c = 1000 \text{ psi}$
 $p_e = 0.2 \text{ psi}$

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H ₂	OF ₂	91	491	4149
H ₂	F ₂	94	489	4809
H ₂	O ₂	84	470	3374
H ₂	NO ₂ ClO ₄	87.5	416	3259
H ₂	NF ₃	94.5	413	4212
H ₂	ClO ₃ F	90	409	3502
H ₂	N ₂ O ₄	89	408	3254
H ₂	H ₂ O ₂	92.5	385	2912
H ₂	ClF ₃	95	373	3985
H ₂	NH ₄ ClO ₄	94	340	2883
N ₂ H ₄	F ₂	69	436	4688
N ₂ H ₄	OF ₂	63	424	4100
N ₂ H ₄	O ₂	49	384	3425
N ₂ H ₄	NF ₃	73	379	4242
N ₂ H ₄	NO ₂ ClO ₄	58	359	3375
N ₂ H ₄	ClO ₃ F	61	358	3478
N ₂ H ₄	N ₂ O ₄	59	354	3262
N ₂ H ₄	H ₂ O ₂	68	348	2916
N ₂ H ₄	ClF ₃	73	345	3882
N ₂ H ₄	NH ₄ ClO ₄	73	318	2969
CH ₂	OF ₂	79	420	4650
CH ₂	F ₂	74	405	4405
CH ₂	O ₂	75	379	3699
CH ₂	NF ₃	78	352	3781
CH ₂	NO ₂ ClO ₄	82.5	349	3587
CH ₂	ClO ₃ F	85	347	3700
CH ₂	N ₂ O ₄	82	345	3453
CH ₂	H ₂ O ₂	88	344	2979
CH ₂	ClF ₃	77	315	3541
CH ₂	NH ₄ ClO ₄	91	309	3001

Table VII Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
UDMH	OF ₂	78	435	4510
UDMH	F ₂	71	426	4342
UDMH	O ₂	68	388	3626
UDMH	NF ₃	76	373	3964
UDMH	ClO ₃ F	77	359	3678
UDMH	NO ₂ ClO ₄	73	358	3567
UDMH	N ₂ O ₄	74	354	3433
UDMH	H ₂ O ₂	82	349	2992
UDMH	ClF ₃	75	337	3794
UDMH	NH ₄ ClO ₄	86	316	3026
Cl ₄ N ₂	O ₂	55	374	4475
Cl ₄ N ₂	OF ₂	65	355	4112
Cl ₄ N ₂	N ₂ O ₄	67	350	4034
Cl ₄ N ₂	H ₂ O ₂	78	350	3257
Cl ₄ N ₂	NO ₂ ClO ₄	67	342	4073
Cl ₄ N ₂	F ₂	85	325	3891
Cl ₄ N ₂	NH ₄ ClO ₄	83	319	3264
Cl ₄ N ₂	ClO ₃ F	68	316	3488
Cl ₄ N ₂	NF ₃	85	301	3680
Cl ₄ N ₂	ClF ₃	87	261	3404
B ₅ H ₉	OF ₂	81.5	466	5215
B ₅ H ₉	F ₂	84	460	5165
B ₅ H ₉	O ₂	72	421	4620
B ₅ H ₉	NF ₃	89	413	4854
B ₅ H ₉	H ₂ O ₂	73	399	3400
B ₅ H ₉	N ₂ O ₄	79	391	4388
B ₅ H ₉	ClO ₃ F	79	390	4447
B ₅ H ₉	NO ₂ ClO ₄	79	389	4502
B ₅ H ₉	ClF ₃	89	368	4543
B ₅ H ₉	NH ₄ ClO ₄	73	370	3000
MgH ₂	F ₂	74	420	4991
MgH ₂	OF ₂	65	394	4337
MgH ₂	NF ₃	78	380	4620
MgH ₂	H ₂ O ₂	42	368	3073
MgH ₂	O ₂	33	357	3216
MgH ₂	N ₂ O ₄	44	349	3265
MgH ₂	NH ₄ ClO ₄	53	348	3080
MgH ₂	ClF ₃	78	347	4465
MgH ₂	NO ₂ ClO ₄	43	346	3288
MgH ₂	ClO ₃ F	49	343	3390

Table VII Continued

Fuel	Oxidizer	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
AlH ₃	F ₂	77	447	5368
AlH ₃	OF ₂	62	431	4447
AlH ₃	H ₂ O ₂	48	424	3923
AlH ₃	O ₂	44	416	4374
AlH ₃	NF ₃	81	407	5006
AlH ₃	N ₂ O ₄	54	401	4292
AlH ₃	NO ₂ ClO ₄	51	397	4252
AlH ₃	NH ₄ ClO ₄	58	393	3837
AlH ₃	ClO ₃ F	55	390	4204
AlH ₃	ClF ₃	80	367	4693
BeH ₂	F ₂	79	501	5194
BeH ₂	H ₂ O ₂	61	498	3884
BeH ₂	OF ₂	70	497	4527
BeH ₂	O ₂	53	492	4004
BeH ₂	N ₂ O ₄	52	462	3446
BeH ₂	NF ₃	81.5	456	4731
BeH ₂	NO ₂ ClO ₄	64	456	4132
BeH ₂	NH ₄ ClO ₄	62	446	3283
BeH ₂	ClO ₃ F	68	446	4173
BeH ₂	ClF ₃	81.5	418	4500
LiH	F ₂	82	445	4886
LiH	OF ₂	77	424	4093
LiH	NF ₃	85.5	392	4384
LiH	ClF ₃	84	360	4109
LiH	ClO ₃ F	76	345	3351
LiH	O ₂	66	342	3309
LiH	H ₂ O ₂	81	341	2711
LiH	NO ₂ ClO ₄	73	333	3292
LiH	NH ₄ ClO ₄	63.5	326	2292
LiH	N ₂ O ₄	74	325	3171

Table VIII

Summary of Maximum Shifting Specific Impulse

 $p_c = 1000 \text{ psi}$ $p_e = 14.696 \text{ psi}$

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	T_c , °K
F ₂	H ₂	89	410	3964
F ₂	BeH ₂	80.5	395	5331
F ₂	LiH	82	363	4886
F ₂	N ₂ H ₄	69	363	4688
F ₂	B ₅ H ₉	82	360	5101
F ₂	AlH ₃	73.5	353	5317
F ₂	UDMH	71	344	4342
F ₂	MgH ₂	72	329	4963
F ₂	CH ₂	72.5	325	4382
F ₂	C ₄ N ₂	85	253	3891
O ₂	H ₂	78	391	2769
O ₂	BeH ₂	54.5	371	4138
O ₂	B ₅ H ₉	70	327	4518
O ₂	AlH ₃	42	318	4299
O ₂	N ₂ H ₄	48	313	3409
O ₂	UDMH	63	310	3614
O ₂	C ₄ N ₂	49	302	4816
O ₂	CH ₂	73	300	3683
O ₂	MgH ₂	31	270	3076
O ₂	LiH	66	263	3309
OF ₂	H ₂	85.5	411	3591
OF ₂	BeH ₂	67	383	4347
OF ₂	B ₅ H ₉	80	367	5169
OF ₂	UDMH	72	351	4460
OF ₂	CH ₂	79	350	4650
OF ₂	N ₂ H ₄	60	345	4037
OF ₂	LiH	77	337	4093
OF ₂	AlH ₃	59	333	4297
OF ₂	MgH ₂	79	305	4516
OF ₂	C ₄ N ₂	68	278	4061

Table VIII Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H ₂ O ₂	BeH ₂	56.5	375	3574
H ₂ O ₂	AlH ₃	48	326	3923
H ₂ O ₂	H ₂	88	322	2404
H ₂ O ₂	B ₅ H ₉	73	316	3400
H ₂ O ₂	N ₂ H ₄	67	286	2923
H ₂ O ₂	UDMH	81	283	3008
H ₂ O ₂	MgH ₂	39	280	3073
H ₂ O ₂	C ₄ N ₂	75	280	3320
H ₂ O ₂	CH ₂	86.5	277	2999
H ₂ O ₂	LiH	81	262	2711
N ₂ O ₄	BeH ₂	50	351	3403
N ₂ O ₄	H ₂	84	342	2660
N ₂ O ₄	AlH ₃	52	308	4226
N ₂ O ₄	B ₅ H ₉	77	306	4266
N ₂ O ₄	N ₂ H ₄	57	291	3257
N ₂ O ₄	UDMH	72	286	3429
N ₂ O ₄	C ₄ N ₂	61	282	4224
N ₂ O ₄	CH ₂	80	276	3444
N ₂ O ₄	MgH ₂	40	265	3073
N ₂ O ₄	LiH	74	250	3171
NF ₃	BeH ₂	81.5	359	4731
NF ₃	H ₂	93	351	3876
NF ₃	B ₅ H ₉	87	326	4809
NF ₃	AlH ₃	78	323	4956
NF ₃	N ₂ H ₄	73	322	4242
NF ₃	LiH	85.5	319	4384
NF ₃	UDMH	76	309	3964
NF ₃	MgH ₂	78	302	4620
NF ₃	CH ₂	78	287	3781
NF ₃	C ₄ N ₂	85	232	3680
ClF ₃	BeH ₂	81.5	329	4500
ClF ₃	H ₂	92	318	3403
ClF ₃	LiH	84	293	4109
ClF ₃	N ₂ H ₄	73	293	3882
ClF ₃	AlH ₃	77	291	4593
ClF ₃	B ₅ H ₉	88	290	4487
ClF ₃	UDMH	75	280	3794
ClF ₃	MgH ₂	78	275	4465
ClF ₃	CH ₂	77	257	3541
ClF ₃	C ₄ N ₂	87	203	3404

Table VIII Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
ClO ₃ F	H ₂	84	344	2744
ClO ₃ F	BeH ₂	68	339	4173
ClO ₃ F	B ₅ H ₉	79	306	4447
ClO ₃ F	AlH ₃	50	301	4029
ClO ₃ F	N ₂ H ₄	59.5	295	3466
ClO ₃ F	CH ₂	81	280	3722
ClO ₃ F	LiH	76	272	3351
ClO ₃ F	MgH ₂	46	260	3237
ClO ₃ F	C ₄ N ₂	62	255	3708
NO ₂ ClO ₄	H ₂	83	349	2713
NO ₂ ClO ₄	BeH ₂	55	346	3394
NO ₂ ClO ₄	AlH ₃	49	305	4175
NO ₂ ClO ₄	B ₅ H ₉	78	302	4432
NO ₂ ClO ₄	N ₂ H ₄	56	295	3363
NO ₂ ClO ₄	UDMH	70	289	3540
NO ₂ ClO ₄	CH ₂	79	278	3586
NO ₂ ClO ₄	C ₄ N ₂	61	276	4272
NO ₂ ClO ₄	MgH ₂	38	263	3114
NO ₂ ClO ₄	LiH	73	258	3292
NH ₄ ClO ₄	BeH ₂	62	340	3283
NH ₄ ClO ₄	AlH ₃	58	302	3837
NH ₄ ClO ₄	H ₂	91	287	2448
NH ₄ ClO ₄	B ₅ H ₉	82	285	3484
NH ₄ ClO ₄	MgH ₂	50	266	3073
NH ₄ ClO ₄	N ₂ H ₄	73	265	2969
NH ₄ ClO ₄	UDMH	85	259	3038
NH ₄ ClO ₄	C ₄ N ₂	80	258	3333
NH ₄ ClO ₄	CH ₂	90.5	252	3016
NH ₄ ClO ₄	LiH	82	249	2687

Table IX

Summary of Maximum Shifting Specific Impulse

 $p_c = 1000 \text{ psi}$ $p_e = 2.0 \text{ psi}$

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
F ₂	H ₂	92	457	4462
F ₂	BeH ₂	80.5	453	5331
F ₂	B ₅ H ₉	84	413	5165
F ₂	LiH	82	410	4886
F ₂	N ₂ H ₄	64	408	4688
F ₂	AlH ₃	75	405	5346
F ₂	UDMH	71	393	4342
F ₂	MgH ₂	74	379	4991
F ₂	CH ₂	72.5	371	4382
F ₂	C ₄ N ₂	85	292	3891
O ₂	H ₂	82	437	3182
O ₂	BeH ₂	53	436	4004
O ₂	B ₅ H ₉	70	379	4518
O ₂	AlH ₃	44	371	4299
O ₂	N ₂ H ₄	49	355	3425
O ₂	UDMH	65	354	3633
O ₂	CH ₂	73	344	3683
O ₂	C ₄ N ₂	52	342	4609
O ₂	MgH ₂	33	316	3216
O ₂	LiH	66	306	3309
OF ₂	H ₂	87	458	3756
OF ₂	BeH ₂	67	445	4347
OF ₂	B ₅ H ₉	80	422	5169
OF ₂	UDMH	75	400	4519
OF ₂	CH ₂	79	393	4650
OF ₂	N ₂ H ₄	63	392	4100
OF ₂	LiH	77	386	4093
OF ₂	AlH ₃	62	386	4447
OF ₂	MgH ₂	69	352	4404
OF ₂	C ₄ N ₂	68	320	4061

Table IX Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H ₂ O ₂	BeH ₂	58	442	3708
H ₂ O ₂	AlH ₃	48	378	3923
H ₂ O ₂	B ₅ H ₉	73	361	3400
H ₂ O ₂	H ₂	91	359	2740
H ₂ O ₂	MgH ₂	42	327	3073
H ₂ O ₂	N ₂ H ₄	68	323	2916
H ₂ O ₂	UDMH	81	321	3008
H ₂ O ₂	C ₄ N ₂	75	319	3320
H ₂ O ₂	CH ₂	88	315	2979
H ₂ O ₂	LiH	81	304	2711
N ₂ O ₄	BeH ₂	50	411	3403
N ₂ O ₄	H ₂	86	381	2891
N ₂ O ₄	AlH ₃	52	358	4226
N ₂ O ₄	B ₅ H ₉	79	353	4388
N ₂ O ₄	N ₂ H ₄	59	329	3262
N ₂ O ₄	UDMH	74	325	3433
N ₂ O ₄	C ₄ N ₂	64	320	4127
N ₂ O ₄	CH ₂	82	316	3453
N ₂ O ₄	MgH ₂	44	310	3265
N ₂ O ₄	LiH	74	290	3171
NF ₃	BeH ₂	81.5	413	4731
NF ₃	H ₂	94.5	390	4212
NF ₃	B ₅ H ₉	88	374	4841
NF ₃	AlH ₃	81	370	5006
NF ₃	LiH	85.5	360	4384
NF ₃	N ₂ H ₄	73	357	4242
NF ₃	UDMH	76	348	3964
NF ₃	MgH ₂	78	346	4620
NF ₃	CH ₂	78	326	3781
NF ₃	C ₄ N ₂	85	269	3680
ClF ₃	BeH ₂	81.5	378	4500
ClF ₃	H ₂	93.5	352	3690
ClF ₃	B ₅ H ₉	88	333	4487
ClF ₃	LiH	84	330	4109
ClF ₃	AlH ₃	80	333	4693
ClF ₃	N ₂ H ₄	73	325	3882
ClF ₃	MgH ₂	78	315	4465
ClF ₃	UDMH	75	314	3794
ClF ₃	CH ₂	77	291	3541
ClF ₃	C ₄ N ₂	87	235	3404

Table IX Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
ClO ₃ F	BeH ₂	68	396	4173
ClO ₃ F	H ₂	87	383	3273
ClO ₃ F	B ₅ H ₉	79	353	4447
ClO ₃ F	AlH ₃	55	350	4204
ClO ₃ F	N ₂ H ₄	61	333	3478
ClO ₃ F	UDMH	75	329	3686
ClO ₃ F	CH ₂	82	319	3734
ClO ₃ F	LiH	76	312	3351
ClO ₃ F	MgH ₂	49	305	3390
ClO ₃ F	C ₄ N ₂	62	289	3708
NO ₂ ClO ₄	BeH ₂	61	406	3866
NO ₂ ClO ₄	H ₂	86	389	3080
NO ₂ ClO ₄	AlH ₃	51	355	4252
NO ₂ ClO ₄	B ₅ H ₉	79	350	4502
NO ₂ ClO ₄	N ₂ H ₄	58	333	3375
NO ₂ ClO ₄	UDMH	73	328	3567
NO ₂ ClO ₄	CH ₂	81	318	3603
NO ₂ ClO ₄	C ₄ N ₂	64	313	4168
NO ₂ ClO ₄	MgH ₂	40	308	3124
NO ₂ ClO ₄	LiH	73	299	3292
NH ₄ ClO ₄	BeH ₂	62	398	3283
NH ₄ ClO ₄	AlH ₃	58	350	3837
NH ₄ ClO ₄	B ₅ H ₉	73	330	3000
NH ₄ ClO ₄	H ₂	92.5	319	2660
NH ₄ ClO ₄	MgH ₂	50	311	3073
NH ₄ ClO ₄	N ₂ H ₄	73	297	2969
NH ₄ ClO ₄	UDMH	86	293	3026
NH ₄ ClO ₄	C ₄ N ₂	83	293	3264
NH ₄ ClO ₄	LiH	82	288	2687
NH ₄ ClO ₄	CH ₂	91	287	3001

Table X

Summary of Maximum Shifting Specific Impulse

Pc = 1000 psi

Pe = 0.2 psi

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
F ₂	BeH ₂	79	501	5194
F ₂	F ₂	94	489	4809
F ₂	B ₅ H ₉	84	460	5165
F ₂	AlH ₃	77	447	5368
F ₂	LiH	82	445	4886
F ₂	N ₂ H ₄	69	436	4688
F ₂	UDMH	71	426	4342
F ₂	MgH ₂	74	420	4991
F ₂	CH ₂	74	405	4405
F ₂	C ₄ N ₂	85	325	3891
O ₂	BeH ₂	53	492	4004
O ₂	H ₂	84	470	3374
O ₂	B ₅ H ₉	72	421	4620
O ₂	AlH ₃	44	416	4374
O ₂	UDMH	68	388	3626
O ₂	N ₂ H ₄	49	384	3425
O ₂	CH ₂	75	379	3699
O ₂	C ₄ N ₂	55	374	4475
O ₂	MgH ₂	33	357	3216
O ₂	LiH	66	342	3309
OF ₂	BeH ₂	70	497	4527
OF ₂	H ₂	91	491	4149
OF ₂	B ₅ H ₉	81.5	466	5215
OF ₂	UDMH	78	435	4510
OF ₂	AlH ₃	62	431	4447
OF ₂	N ₂ H ₄	63	424	4100
OF ₂	LiH	77	424	4093
OF ₂	CH ₂	79	420	4650
OF ₂	MgH ₂	65	394	4337
OF ₂	C ₄ N ₂	65	355	4112

Table X Continued

Oxidizer	Fuel	Wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
H ₂ O ₂	BeH ₂	61	498	3884
H ₂ O ₂	AlH ₃	48	424	3923
H ₂ O ₂	B ₅ H ₉	73	399	3400
H ₂ O ₂	H ₂	92.5	385	2912
H ₂ O ₂	MgH ₂	42	368	3073
H ₂ O ₂	C ₄ N ₂	78	350	3257
H ₂ O ₂	UDMH	82	349	2992
H ₂ O ₂	N ₂ H ₄	68	348	2916
H ₂ O ₂	CH ₂	88	344	2979
H ₂ O ₂	LiH	81	341	2711
N ₂ O ₄	BeH ₂	52	462	3446
N ₂ O ₄	H ₂	89	408	3254
N ₂ O ₄	AlH ₃	54	401	4292
N ₂ O ₄	B ₅ H ₉	79	391	4388
N ₂ O ₄	N ₂ H ₄	59	354	3262
N ₂ O ₄	UDMH	74	354	3433
N ₂ O ₄	C ₄ N ₂	67	350	4034
N ₂ O ₄	MgH ₂	44	349	3265
N ₂ O ₄	CH ₂	88	344	2979
N ₂ O ₄	LiH	74	325	3171
NF ₃	BeH ₂	81.5	456	4731
NF ₃	H ₂	94.5	413	4212
NF ₃	B ₅ H ₉	89	413	4854
NF ₃	AlH ₃	81	407	5006
NF ₃	LiH	85.5	392	4384
NF ₃	MgH ₂	78	380	4620
NF ₃	N ₂ H ₄	73	379	4242
NF ₃	UDMH	76	373	3964
NF ₃	CH ₂	78	352	3781
NF ₃	C ₄ N ₂	85	301	3680
ClF ₃	BeH ₂	81.5	418	4500
ClF ₃	H ₂	95	373	3985
ClF ₃	B ₅ H ₉	89	368	4543
ClF ₃	AlH ₃	80	367	4693
ClF ₃	LiH	84	360	4109
ClF ₃	MgH ₂	78	347	4465
ClF ₃	N ₂ H ₄	73	345	2969
ClF ₃	UDMH	75	337	3794
ClF ₃	CH ₂	77	315	3541
ClF ₃	C ₄ N ₂	87	261	3404

Table X Continued

Oxidizer	Fuel	wt. % Oxidizer	Shifting Isp, Seconds	Tc, °K
ClO ₃ F	BeH ₂	68	446	4173
ClO ₃ F	H ₂	90	409	3502
ClO ₃ F	AlH ₃	55	390	4204
ClO ₃ F	B ₅ H ₉	79	390	4447
ClO ₃ F	UDMH	77	359	3678
ClO ₃ F	N ₂ H ₄	61	358	3478
ClO ₃ F	CH ₂	85	347	3700
ClO ₃ F	LiH	76	345	3351
ClO ₃ F	MgH ₂	49	343	3390
ClO ₃ F	C ₄ N ₂	68	316	3488
NO ₂ ClO ₄	BeH ₂	64	456	4132
NO ₂ ClO ₄	H ₂	87.5	416	3259
NO ₂ ClO ₄	AlH ₃	51	397	4252
NO ₂ ClO ₄	B ₅ H ₉	79	389	4502
NO ₂ ClO ₄	N ₂ H ₄	58	359	3375
NO ₂ ClO ₄	UDMH	73	358	3567
NO ₂ ClO ₄	CH ₂	82.5	349	3587
NO ₂ ClO ₄	MgH ₂	43	346	3288
NO ₂ ClO ₄	C ₄ N ₂	67	342	4073
NO ₂ ClO ₄	LiH	73	333	3292
NH ₄ ClO ₄	BeH ₂	62	446	3283
NH ₄ ClO ₄	AlH ₃	58	393	3837
NH ₄ ClO ₄	B ₅ H ₉	73	370	3000
NH ₄ ClO ₄	MgH ₂	53	348	3080
NH ₄ ClO ₄	H ₂	94	340	2883
NH ₄ ClO ₄	LiH	62	326	2227
NH ₄ ClO ₄	C ₄ N ₂	83	319	3264
NH ₄ ClO ₄	N ₂ H ₄	73	318	2969
NH ₄ ClO ₄	UDMH	86	316	3026
NH ₄ ClO ₄	CH ₂	91	309	3001

B. Discussion of the Results

1. Liquid Hydrogen Systems

Both liquid fluorine and liquid oxygen difluoride were found to be excellent oxidizers for liquid hydrogen, with the latter yielding slightly higher maximum performance. On the fuel-rich side of maximum performance, oxygen difluoride is the superior oxidizer. However, the performance drops off more gradually on the oxidizer-rich side using liquid fluorine. Combustion temperatures are comparable in both systems up to the point of maximum specific impulse. Beyond that, on the oxidizer-rich side, the H_2-F_2 system burns with the hotter flame. The prime energy source is the formation of HF, with the formation of H_2O also contributing in the H_2-OF_2 system. It is interesting to note that the maximum performance occurs on the fuel-rich side of stoichiometric combustion, indicating the value of hydrogen gas as a working fluid. In fact, dissociation is relatively slight in both systems on the fuel-rich side of peak performance, causing only a slight difference in the frozen and shifting specific impulse. However, as the systems become oxidizer-rich, the degree of chamber dissociation increases rapidly, and the spread between frozen and shifting performance increases accordingly.

Liquid oxygen rates closely behind oxygen difluoride and liquid fluorine as an energetic oxidizer for liquid hydrogen. Again, the maximum performance occurs on the fuel-rich side of stoichiometric combustion. Of course, the principal source of energy is the formation of water. Dissociation, and the corresponding spread between shifting and frozen impulse, increases

as the system becomes oxidizer-rich. The most significant difference between the H_2-O_2 system and previous two is the lower combustion temperature of H_2-O_2 . Although somewhat higher performance may be achieved by oxidizing hydrogen to HF rather than to H_2O , a considerably hotter flame must be tolerated. This characteristic is also displayed by the other less-energetic oxidizers, in which nitrogen and chlorine serve as carrier atoms for oxygen and fluorine.

Next in order of performance are NF_3 , NO_2ClO_4 , ClO_3F , and N_2O_4 . These four oxidizers are closely grouped, yielding maximum specific impulses of 351, 349, 344, and 341 seconds respectively at an exhaust pressure of one atmosphere. Furthermore, the shifting specific impulse spread is narrowed to five seconds at an exhaust pressure of 0.2 psi. The halogens, chlorine and fluorine, appear as HCl and HF in the products of combustion. Both constitute energy sources, although HCl is considerably less valuable in this respect. Also, its higher molecular weight makes it relatively less desirable as a working fluid. In each system, the peak performance still occurs on the fuel-rich side of stoichiometric combustion. This further illustrates the value of only partially oxidizing the hydrogen in order to obtain the maximum useful energy. In the $H_2-NO_2ClO_4$ and the $H_2-N_2O_4$ systems, most of the nitrogen appears as N_2 in the combustion products. However, upon reacting fuel-rich, considerable amounts of NH_3 are formed at the lower exhaust pressures. The lower pressures, coupled with the corresponding lower temperatures, promote the formation of this larger molecule. In each case, the spread between frozen and shifting specific impulse is considerably greater on the oxidizer-rich side of the performance

curve. As before, this is attributed to the greater degree of dissociation at the higher combustion temperatures.

Hydrogen peroxide and chlorine trifluoride constitute the next oxidizer performance plateau. Chemically, the $H_2-H_2O_2$ system differs from the H_2-O_2 system only in that the oxygen is partially reacted with hydrogen in H_2O_2 . Whereas the heat-of-formation of liquid oxygen is -3.08 Kcal/mole at its boiling point, that of H_2O_2 is -44.84 Kcal/mole at 298°K. This means that a substantial amount of useful energy has been lost in H_2O_2 . The loss in shifting specific impulse is 69 seconds at an exhaust pressure of 1 atmosphere, 78 seconds at 2.0 psi, and 85 seconds at 0.2 psi. Similarly, ClF_3 differs from NF_3 in that chlorine has replaced nitrogen as a carrier for fluorine. The more exothermic heat-of-formation for ClF_3 indicates that the Cl-F bond is stronger, and therefore less desirable in a propellant ingredient. The loss in maximum specific impulse is 33 seconds when exhausting to one atmosphere, 38 seconds at 2.0 psi, and 40 seconds at 0.2 psi. The lower molecular weight of nitrogen also contributes to these performance spreads.

Ammonium perchlorate was found to be the least energetic oxidizer for liquid hydrogen. This was to be expected in view of its relatively exothermic heat-of-formation of -69.42 Kcal/mole and the presence of both nitrogen and chlorine as carrier elements. The formation of H_2O and HCl constitute the principal energy sources. On the other hand, H_2 and N_2 are the principal unreacted working fluids. However, again large concentrations of NH_3 are obtained at the sub-atmospheric exhaust pressures when the stoichiometry is fuel-rich. The ClO_4 moiety is common to both ammonium

perchlorate and nitronium perchlorate. However, the marked superiority of NO_2ClO_4 as an oxidizer is quite apparent from the performance curves. This stems from the substantially more endothermic heat-of-formation of NO_2ClO_4 as well as the greater quantity of available oxygen. Ammonium perchlorate, like hydrogen peroxide, may be thought of as low-energy monopropellant since both hydrogen and oxygen are available in the same molecule for subsequent chemical reaction.

2. Hydrazine Systems

Using hydrazine as the rocket fuel, liquid fluorine is the most energetic oxidizer. Although N_2H_4 has an endothermic heat-of-formation, there is a substantial drop in performance caused by the introduction of nitrogen as a carrier element. Whereas the $\text{H}_2\text{-F}_2$ system yields a maximum Isp of 410 seconds at $p_c/p_e = 68$, the $\text{N}_2\text{H}_4\text{-F}_2$ system yields only 363 seconds. Chemically, the $\text{N}_2\text{H}_4\text{-F}_2$ system is comparable to the $\text{H}_2\text{-NF}_3$ system. Of these, the $\text{N}_2\text{H}_4\text{-F}_2$ system is superior because of the endothermic heat-of-formation of hydrazine. This points out the desirability of utilizing the most endothermic reactants for propellant ingredients, providing other considerations are equal. Furthermore, the endothermic heat-of-formation of hydrazine causes a higher flame temperature than using liquid hydrogen as the fuel. Subsequently, dissociation is greater and the spread between frozen and shifting Isp is greater, on a percentage basis. These generalizations apply to the use of each oxidizer with hydrazine.

Oxygen difluoride was found to be the second most energetic oxidizer for use with hydrazine. The principal exhaust products for this system are HF , H_2O , H_2 , and N_2 . Next in order of performance are nitrogen trifluoride

and liquid oxygen. Like the H_2-NF_3 and the $N_2H_4-F_2$ systems, the $N_2H_4-NF_3$ system is composed of only nitrogen, hydrogen, and fluorine. However, in this latter system nitrogen serves as a carrier for both hydrogen and fluorine. Consequently, the performance is lower. The still lower performance of $N_2H_4-O_2$, relative to $N_2H_4-NF_3$, indicates that the presence of nitrogen in the fuel is more detrimental when oxidizing with oxygen than when utilizing fluorine. This trend is maintained with the other oxidizers considered. Both ClO_3F and ClF_3 , the other fluorine-containing oxidizers, ranked relatively more potent with hydrazine than with liquid hydrogen although the absolute performances were lower. Very little ammonia was present in the combustion products of the hydrazine-oxygen system, even on the fuel-rich side, despite the presence of large quantities of nitrogen and hydrogen gases. This was due to the higher exhaust temperatures in this system. In general, NH_3 is a significant exhaust specie only below $600^\circ K$ at a pressure of 2.0 psi and only below $500^\circ K$ at a pressure of 0.2 psi.

Perchloryl fluoride and nitronium perchlorate yielded equivalent performances with hydrazine. The presence of fluorine in ClO_3F offset the more endothermic heat-of-formation of NO_2ClO_4 . With liquid hydrogen, the latter oxidizer was superior by 5-7 seconds. Furthermore, the presence of fluorine in ClO_3F accounted for a slightly higher combustion temperature, again offsetting the higher heat-of-formation of NO_2ClO_4 . Neither system was very highly dissociated, even on the oxygen-rich sides. The maximum combustion temperatures occurred near the stoichiometry of maximum specific impulse.

Closely following perchloryl fluoride and nitronium perchlorate in order of performance are chlorine trifluoride, nitrogen tetroxide, and hydrogen peroxide respectively. The most noticeable contrast in the performance curves of the three systems is the sharp drop-off on the oxidizer-rich side of the ClF_3 system. In general, this is typical of the behavior of ClF_3 systems and, to a lesser extent, NF_3 systems. However, this is more pronounced with some of the other fuels, as will be shown later. Ammonium perchlorate is the least energetic oxidizer, for the same reasons cited previously.

3. Polyethylene Systems

Polyethylene, with the empirical formula $(\text{CH}_2)_x$, was chosen as the prototype fuel to represent the hydrocarbon family. Having the highest H/C ratio of any of the aliphatic hydrocarbons, CH_2 represents the maximum energy source from this family. Furthermore, its stoichiometry corresponds to that of diethylcyclohexane, $\text{C}_{10}\text{H}_{20}$, although the performance of the latter is somewhat less because of its slightly more exothermic heat-of-formation.

Oxygen difluoride was found to be the best oxidizer for CH_2 . One of the prime reasons for this is the ideal stoichiometry for the formation of HF and CO as products of combustion. At the point of maximum specific impulse, the HF is slightly dissociated into H, F, and H_2 because of the high combustion temperature. In the $\text{CH}_2\text{-OF}_2$ system, greater performance is obtained by forming the maximum amount of HF and CO than by under-oxidizing in order to obtain hydrogen. By under-oxidizing, large quantities of solid carbon are formed in the exhaust. Over-oxidizing tends to promote

the formation of carbon dioxide as well as allowing F and F₂ to emerge uncombined. The spread between frozen and shifting impulse reaches a maximum at the point of maximum performance.

Next in order of performance is liquid fluorine. In this case, HF alone constitutes energy source with all the carbon emerging as the unreacted solid element. This further emphasizes the value of HF as a product of combustion. On the oxidizer-rich side of the system, solid carbon is still the predominant carbon-containing specie. Only small quantities of fluorocarbons were present in the exhaust. Liquid oxygen, the next best oxidizer, is distinctly inferior to either OF₂ or F₂. In the CH₂-O₂ system, the predominant chemical equilibrium is the water-gas shift reaction. During expansion, some of the carbon monoxide and water react to form carbon dioxide and hydrogen. Under-oxidizing reduces performance because CO and CO₂ do not supply sufficient energy to the low molecular weight hydrogen gas. On the other hand, over-oxidizing lowers performance because too much CO₂ and H₂O are present. Thus, more energy may be obtained from a hydrocarbon by its combustion with a combination of oxygen and fluorine than with either oxygen or fluorine alone.

Nitrogen trifluoride, perchloryl fluoride, nitronium perchlorate, hydrogen peroxide, and nitrogen tetroxide are closely grouped in the next energy level. At pc/pe = 68 the performance spread for this group is 11 seconds while at pc/pe = 5000 it is only 7 seconds. In view of this relatively small spread in specific impulse, the considerably higher density of NO₂ClO₄ makes it the best of the group for overall missile performance. Chemically, the ClO₃F-CH₂ system is the most complex with HF, HCl, H₂O, CO₂.

and CO all contributing useful energy. Completing the ranking of the oxidizers are ClF_3 and NH_4ClO_4 . Maximum performance occurs in the ClF_3 - CH_2 system near the point of maximum formation of HF and HCl. However, the large quantity of unreacted carbon makes the system unattractive from an energy standpoint.

With the exception of OF_2 , every oxidizer behaves poorer with CH_2 than with N_2H_4 . Of course, the performance is still lower than when reacting each oxidizer with liquid hydrogen. Thus, carbon appears less desirable than either hydrogen or nitrogen as a propellant ingredient, from the energy viewpoint. Also, oxygen appears to be essential for the energetic oxidation of carbon.

4. UDMH Systems

The use of unsymmetrical dimethyl hydrazine as a fuel introduces carbon, nitrogen, and hydrogen simultaneously into a propellant system. Although two of hydrazine's four hydrogen atoms are replaced by methyl groups in UDMH, there is less than 1 Kcal difference in the heat-of-formation of the two molecules. Thus, the relative performances of hydrazine and UDMH provide a good measure of the effect of carbon on performance.

Again, OF_2 is the best oxidizer with F_2 following closely. Liquid oxygen ranks third, but considerably below the first two. In fact, the UDMH- O_2 system exceeds the UDMH- NF_3 system by only one second at $p_c/p_e = 68$. However, at $p_c/p_e = 5000$ this spread is 15 seconds. This further shows that the presence of nitrogen is more detrimental to the C-H-O system than to the C-H-F system. In general, the same comments made previously on stoichiometry and reaction products apply here. In a C-H-O-N system, maximum performance

usually lies somewhere between balancing the reactants to CO and H₂O and to CO₂ and H₂O. In a C-H-F system, the greatest energy release occurs when all the hydrogen and fluorine combine to form HF.

The other oxidizers, in order of their performance with UDMH, are perchloryl fluoride, nitronium perchlorate, nitrogen tetroxide, hydrogen peroxide, chlorine trifluoride, and ammonium perchlorate. It is interesting to note that the performance of the various UDMH systems is only 3-6 seconds lower than that of corresponding hydrazine systems at $pc/pe = 68$ for any oxidizer containing oxygen. At $pc/pe=5000$, the difference is even less. In fact, the performance of UDMH-O₂ exceeds that of N₂H₄-O₂ at $pc/pe = 5000$. The same holds when NF₃, F₂, and ClF₃ are the oxidizers. Although the Isp spread between UDMH and hydrazine varies from 13-19 seconds at $pc/pe = 68$, the variation is only 6-10 seconds at $pc/pe = 5000$. Chamber temperatures are slightly higher when UDMH is reacted with oxygen-containing oxidizers than when hydrazine is the fuel. The opposite is true when fluorine is the sole oxidizer. Although the presence of carbon in UDMH does not appreciably reduce the performance below that attainable from hydrazine, two compensating factors must be considered. One is the small change in heat-of-formation of the fuel. Usually, the addition of alkyl groups to a fuel makes its heat-of-formation more exothermic. The second factor is the greater percentage of hydrogen in UDMH. This tends to offset the deleterious effects of carbon.

In the UDMH-F₂, UDMH-NF₃, and UDMH-ClF₃ systems, practically all of the carbon emerged as the unreacted solid element. Even when operating oxidizer-rich, only small concentrations of fluorocarbons appeared. Of these, CF₄ was the predominant one. This increased in concentration as both temperature

and pressure decreased, but was always appreciably less than the concentration of solid carbon. The fluorocarbons appear to be very poor products of combustion, both as an energy source and as a working fluid.

5. Dicyanoacetylene Systems

Dicyanoacetylene constitutes a unique prototype fuel in that it has an unusually endothermic heat-of-formation and is composed of only carbon and nitrogen. Thus, eight of the ten C_4N_2 systems are void of hydrogen. With O_2 , H_2O_2 , N_2O_4 , NO_2ClO_4 , and NH_4ClO_4 , the performance of C_4N_2 was found comparable to that of CH_2 . However, the combustion temperatures were considerably hotter because of the relatively slight dissociation of the combustion products. When hydrogen was absent, CO and N_2 were the principal combustion products, and the maximum specific impulse occurred when reacting slightly oxygen-rich of this stoichiometry. The carbon nitrides CN and C_2N_2 were formed in only minor concentrations, being practically nonexistent except on the fuel-rich side of the C_4N_2 - N_2O_4 system.

The presence of fluorine in these hydrogen-free systems caused a marked drop in performance. This was true even for OF_2 and ClO_3F in which oxygen also is present. Using F_2 , NF_3 , and ClF_3 as oxidizers, the fluorocarbons were the principal energy sources. In the chamber CF_3 was most predominant while CF_4 became increasingly more important as the temperature and pressure were reduced. Although combustion temperatures in excess of $3000^\circ K$ were obtained, the performance was very poor. Thus, the C_4N_2 series emphasizes that oxygen is essential for the energetic oxidation of carbon and that a large endothermic heat-of-formation cannot surpass the value of hydrogen in a propellant formulation.

6. Pentaborane Systems

Pentaborane, one of five light metal hydrides selected for this study, represents the boron hydride family. Both oxygen difluoride and liquid fluorine were found to be excellent oxidizers for pentaborane. The former system yields a specific impulse of 367 seconds at an exhaust pressure of one atmosphere while the latter yields 360 seconds under the same conditions. However, the performance of the $\text{OF}_2 - \text{B}_5\text{H}_9$ system is contingent upon the formation of BOF as a product of combustion. Although this oxyhalide has never been isolated, the trimer has been synthesized and its heat-of-formation evaluated. Because of its relatively simple structure, the probability of BOF occurring in a high temperature equilibrium mixture is good. A heat-of-formation of -150 Kcal/mole at 298°K was used in this study. If BOF is not considered as a product of combustion, the maximum specific impulse of the $\text{OF}_2 - \text{B}_5\text{H}_9$ drops to 350 seconds. This peak occurs at 77% by weight oxidizer and still constitutes a very energetic system. Both oxygen difluoride and liquid fluorine produce combustion temperatures in excess of 5000°K at their points of maximum specific impulse. Because of these high temperatures, both systems are highly dissociated. For the $\text{F}_2 - \text{B}_5\text{H}_9$ system, HF and BF are the principal species in the chamber. During expansion through the nozzle, BF_3 and H_2 also become major products of combustion. This is particularly true at the sub-atmospheric exhaust pressures.

For the $\text{OF}_2 - \text{B}_5\text{H}_9$ system, BOF and HF are the principal combustion products, with hydrogen gas increasing in concentration during expansion.

Both liquid oxygen and nitrogen trifluoride are also good oxidizers for pentaborane. Closely following is hydrogen peroxide. Although somewhat less energetic, the $\text{H}_2\text{O}_2\text{-B}_5\text{H}_9$ system has a combustion temperature approximately 1100°K less than that of $\text{O}_2\text{-B}_5\text{H}_9$ and approximately 1400°K less than that of $\text{NF}_3\text{-B}_5\text{H}_9$. The combustion products of the latter system were essentially the same as those of the $\text{F}_2\text{-B}_5\text{H}_9$ system, except nitrogen gas was also present. Metaboric acid, HBO_2 , was the principal boron-containing specie not only in the $\text{O}_2\text{-B}_5\text{H}_9$ and $\text{H}_2\text{O}_2\text{-B}_5\text{H}_9$ systems but also in the others containing boron, oxygen, and hydrogen in the absence of fluorine. Liquid boric oxide becomes a major specie only when operating fuel-rich at lower temperatures.

Nitrogen tetroxide, perchloryl fluoride, and nitronium perchlorate constitute the next performance plateau with chlorine trifluoride and ammonium perchlorate being the least energetic. Despite the strong affinity of boron for fluorine, chlorine trifluoride is not a particularly potent oxidizer for the boron hydrides. This constitutes still further evidence of the undesirability of the Cl-F bond in propellant ingredients relative to the N-F or O-F bond. The oxidizers N_2O_4 , NO_2ClO_4 , and NH_4ClO_4 possess gradually-sloping performance curves on the fuel-rich side of maximum performance. This may be attributed to the formation of crystalline boron nitride and liquid boric oxide under these conditions.

When oxidizing pentaborane with F_2 , NF_3 , or ClF_3 , the maximum specific impulse occurs near the stoichiometry for which all the boron and fluorine exist as BF_3 . When oxygen is the only oxidizer, the stoichiometric reaction of all the boron and oxygen to HBO_2 will define the peak performance very

closely. In the $\text{OF}_2\text{-B}_5\text{H}_9$ system, maximum performance occurs near the point of stoichiometric reaction to HF and BOF .

Whereas fluorine has a very strong affinity for boron, that of chlorine is not as great. Large concentrations of the boron chlorides are rare, with hydrogen chloride being formed in preference. Also, the boron interhalides are not formed in large quantities relative to the boron fluorides.

7. Aluminum Hydride Systems

In general, the performance of aluminum hydride with the various oxidizers closely parallels that of pentaborane. The most noticeable differences are OF_2 , O_2 , H_2O_2 , and NH_4ClO_4 . Whereas the first two oxidizers are superior with pentaborane, the latter two yields higher performances with AlH_3 . Combustion temperatures are also comparable, with those for the AlH_3 systems tending to be slightly higher.

The principal energy source of the aluminum-oxygen systems is condensed Al_2O_3 , which has a highly exothermic heat-of-formation. Hydrogen gas is the main constituent of the working fluid. Using O_2 , H_2O_2 , N_2O_4 , and NH_4ClO_4 as oxidizers for AlH_3 , the maximum specific impulse occurs near the stoichiometry for which all the aluminum and oxygen react to Al_2O_3 . The peak performance of the $\text{NO}_2\text{ClO}_4\text{-AlH}_3$ system is defined by reacting stoichiometrically to Al_2O_3 and AlCl .

Using fluorine as the oxidizer for aluminum, the point of maximum performance is more difficult to predict. With F_2 , NF_3 , and ClF_3 , the peak performance occurs between reacting to AlF_3 and AlF_3 plus HF . The reaction products are usually highly dissociated, with AlF , AlF_2 , and AlF_3

all existing in appreciable quantities. The first of these predominates in the chamber while the last is most significant at exhaust conditions. Of course, HF also exists in large concentrations, particularly in the chamber. During expansion, the quantity of HF decreases in favor of AlF_3 . In the $\text{AlH}_3\text{-ClF}_3$ system, the aluminum chlorides and mixed halides are formed. The oxyhalide AlOF is a minor specie and does not possess the same importance of its boron counterpart, BOF .

As in the case of boron, fluorine appears superior to oxygen as an oxidizer for aluminum. Liquid fluorine ranks as the best oxidizer for aluminum hydride, followed by OF_2 , H_2O_2 , NF_3 , and O_2 . Closely grouped behind these oxidizers are N_2O_4 , NO_2ClO_4 , ClO_3F , and NH_4ClO_4 . It is interesting to note that ammonium perchlorate is almost as good an oxidizer as nitronium perchlorate and nitrogen tetroxide with AlH_3 . This is probably due, in part, to the relatively small quantities of hydrogen available for working fluid in the latter two systems. Since Al_2O_3 is a relatively large molecule with a molecular weight of 102, a considerable amount of low molecular weight gas must accompany its formation to obtain high performance. Thus, if another source of working fluid, such as H_2 or N_2H_4 , were added to the $\text{AlH}_3\text{-N}_2\text{O}_4$ and $\text{AlH}_3\text{-NO}_2\text{ClO}_4$ systems, the performance could probably be increased. The fact that hydrogen peroxide excels over liquid oxygen as an oxidizer for AlH_3 further emphasizes the importance of having large quantities of working fluid to accompany the formation of highly exothermic condensed phases, such as Al_2O_3 .

The spread between frozen and shifting specific impulse is considerably greater in the aluminum-fluorine systems than in the aluminum-

oxygen systems. Upon expanding to sub-atmospheric exhaust pressures, this spread becomes greater.

8. Beryllium Hydride Systems

Beryllium hydride was found to be an extremely energetic fuel. Only liquid hydrogen yielded greater performance at $p_c/p_e = 68$ with the oxidizers F_2 , O_2 , OF_2 , and NO_2ClO_4 . However, at $p_c/p_e = 5000$ beryllium hydride was the most energetic fuel in every case. Under these conditions the BeH_2-F_2 system yielded a maximum specific impulse of 501 seconds, exceeding that of the H_2-F_2 system by 12 seconds.

Using fluorine as the oxidizer for beryllium hydride, the principal combustion products are BeF_2 and H_2 . Because of the high combustion temperatures, a significant degree of dissociation exists in the chamber. Hydrogen atoms, beryllium gas, and hydrogen fluoride are each present in fairly large amounts. Upon expansion, these shift to form BeF_2 and H_2 , releasing considerable energy in the process. The maximum performance occurs near the point at which all beryllium and fluorine react to form BeF_2 . Liquid fluorine, nitrogen trifluoride, and chlorine trifluoride each follow this pattern.

With oxygen as the oxidizer for beryllium hydride, the principal combustion products are condensed beryllium oxide and hydrogen. As in the case of the aluminum-oxygen system, large quantities of working fluid must accompany the formation of the highly exothermic BeO in order to realize the optimum performance. This is illustrated by the fact that hydrogen peroxide yields greater performance than liquid oxygen with beryllium hydride, and ammonium perchlorate is almost as energetic as

nitronium perchlorate. In the beryllium-oxygen system, the maximum specific impulse was found to occur on the fuel-rich side of stoichiometric combustion to BeO. This varied from 5% by weight oxidizer in the case of the BeH₂-H₂O₂ system to 18% in the case of the BeH₂-N₂O₄ system. The beryllium systems are different from the other metal hydride systems in that fairly significant quantities of the metallic gas exists at the point of maximum specific impulse. Like hydrogen gas, the beryllium gas serves as additional working fluid to which the energy of formation of BeO may be transferred. Furthermore, when nitrogen was present in the oxidizer, significant quantities of solid beryllium nitride were present at the point of maximum specific impulse. The affinity of beryllium for chlorine was also found to be quite high. In the chamber, BeCl replaces HCl as the predominant chloride, particularly at high temperatures. In the exhaust, BeCl₂ is the principal chloride. The gaseous polymers of the beryllium oxide were found to exist in relatively small quantities, having only a very slight, if not negligible, influence on performance. The principal beryllium-oxygen gas specie is beryllium hydroxide, BeOH. Another feature of the beryllium systems is the relatively higher performance available upon expanding to low pressures. The gain in performance over the other light metal systems is greater at the lower exhaust pressures.

Like the other chemical systems studied, the spread between frozen and shifting specific impulse is considerably greater when carrier elements, such as nitrogen and chlorine, are not present. The spread varies from as much as 40 seconds in the BeH₂-F₂ system to as little as 10 seconds in the BeH₂-NH₄ClO₄ system.

9. Lithium Hydride Systems

Lithium hydride was found to be considerably more energetic with fluorine than with oxygen. In fact, liquid fluorine, oxygen difluoride, nitrogen tetroxide, and chlorine trifluoride all yielded substantially higher performance with lithium hydride than did any of the all-oxygen oxidizers. Combustion temperatures ranged between 4000°K and 5000°K. The spread in performance was relatively small for liquid oxygen, hydrogen peroxide, nitronium perchlorate, ammonium perchlorate, and nitrogen tetroxide, varying from 263 to 250 seconds at $pc/pe = 68$.

The maximum specific impulse of the $LiH-F_2$ and $LiH-NF_3$ systems occurs near the point of stoichiometric combustion to LiF and HF . However, peak performance for the interhalide ClF_3 is defined by stoichiometric combustion to HF , LiF , and $LiCl$. The affinity of chlorine for lithium appears stronger than for any of the other light metals. Lithium chloride is the principal chlorine-containing specie in the products of combustion. Both LiF and HF are highly exothermic energy sources as well as fairly low molecular weight working fluids. The dimer and trimer of lithium fluoride become significant exhaust species at low pressures and temperatures. Although their concentrations are negligible in the combustion chamber, these polymers may constitute more than 50% of the lithium fluoride at the sub-atmospheric exhaust conditions. The dimer of lithium chloride was found to be considerably less significant.

For the oxygen-containing oxidizers, maximum performance usually occurs near the point of stoichiometric combustion to Li_2O and H_2O .

One exception is hydrogen peroxide, for which the peak is very close to stoichiometric combustion to LiOH and H_2O . In all of these systems, lithium hydroxide is the principal lithium-containing gas specie. Liquid lithium oxide and water are the other major products of combustion. Upon reacting fuel-rich, considerable quantities of hydrogen gas are also evolved. This accounts for the gradual slope of the performance curves over the fuel-rich composition range. Once again H_2O_2 and NH_4ClO_4 , with relatively exothermic heats-of-formation, yield almost as much performance as their more oxygen-rich counterparts, O_2 and NO_2ClO_4 . Again this points out the necessity for a low molecular weight working fluid to accompany the formation of an exothermic condensed phase, such as liquid lithium oxide. Although lithium hydride is competitive with pentaborane, aluminum hydride and hydrazine when reacted with F_2 , NF_3 , and ClF_3 , it is quite inferior with the oxygen-containing oxidizers.

10. Magnesium Hydride Systems

Magnesium hydride was found to be somewhat like lithium hydride in that superior performance is obtained by oxidizing with fluorine. However, this effect is not as pronounced as with lithium hydride. Although liquid fluorine yielded the greatest performance with magnesium hydride, this was not exceptionally energetic. At $p_c/p_e = 68$, a maximum specific impulse of 329 seconds was obtained. This occurred near the point of stoichiometric combustion to MgF_2 and HF . The same held for the NF_3 - MgH_2 system. With chlorine trifluoride, maximum performance was achieved by reacting to HF , HCl , and MgF_2 .

Hydrogen peroxide yielded the best performance of the oxygen-containing oxidizers. Closely grouped behind were O_2 , NH_4ClO_4 , N_2O_4 and NO_2ClO_4 respectively. Again, the lack of low molecular weight working fluid limited the usefulness of O_2 and NO_2ClO_4 . Condensed magnesium oxide, hydrogen gas, water, and magnesium hydroxide constituted the principal combustion products. The first two are particularly predominant over the entire range of combustion stoichiometry. As in the case of lithium and beryllium, the predominant gas metal-oxygen specie was the metallic hydroxide. One outstanding characteristic of the magnesium-oxygen systems is the very gradual slope of the performance curves over relatively wide ranges of composition.

11. General Conclusions

Of the non-metallic fuels, liquid hydrogen was found to yield the greatest performance with each of the ten oxidizers. This was to be expected because of the energetic reactions of hydrogen with both oxygen and fluorine. In most cases, the remaining order of performance was hydrazine, UDMH, polyethylene, and dicyanoacetylene. From this, it may be concluded that the N-H bond is more desirable than the C-H bond in a rocket fuel. Most important of all is that the hydrogen content of the fuel be high. Even the presence of a highly endothermic reactant, such as dicyanoacetylene, cannot overcome the value of hydrogen as an ingredient element. Of the metallic fuels, beryllium hydride was clearly superior, both with fluorine and oxygen as oxidizers. Pentaborane and aluminum hydride were found to be highly energetic with both oxygen and fluorine. Lithium appears to be a desirable fuel ingredient if oxidized

with fluorine. However, neither lithium nor magnesium yields high performance if combined with oxygen.

Both fluorine and oxygen difluoride were found to be highly energetic oxidizers. Thus, it may be concluded that fluorine or mixtures of fluorine and oxygen yield greater performance than oxygen alone. An exception occurs when the carbon-to-hydrogen ratio of the ingredients is large. With both metallic and non-metallic fuels, the performance of oxygen difluoride exceeded that of nitrogen trifluoride which, in turn, surpassed that of chlorine trifluoride. These data indicate that O-F bonding, N-F bonding, and Cl-F bonding are preferred in that order.

The relative ranking of the propellant systems at an exhaust pressure of one atmosphere was not always the same at the lower exit pressures. For example, although BeH_2 was the most energetic fuel in six of the ten cases at $p_c/p_e = 68$, it excelled in all ten cases at $p_c/p_e = 5000$. In general, expansion to sub-atmospheric pressures yielded relatively more performance for the metallic fuels. Any similar changes in the ranking of the oxidizers was not as sharply pronounced.

APPENDICES

APPENDIX A

SAMPLE CALCULATION USING THE METHOD OF EQUILIBRIUM CONSTANTS

1. Statement of the Problem

Ingredient	Weight %	Moles/100 gm Propellant	MW	ΔH_{f298} Kcal/mole	ρ g/cc
NH_4ClO_4	62	0.5277	117.497	-69.42	1.95
Al	23	0.8528	26.97	0	2.7
$(\text{CH}_2)_x$	15	1.0694	14.026	0	0.78

Chamber Pressure = 1000 PSIA

Exhaust Pressure = 14.7 PSIA

Density of Propellant = 1.7715 g/cc

Heat-of-Formation of Propellant = -36.633 Kcal/100 gm

Concentration of Ingredients per 100 gm propellant:

C = 1.0694 gm-atoms

H = 4.2496 gm-atoms

O = 2.1107 gm-atoms

N = 0.5277 gm-atoms

Cl = 0.5277 gm-atoms

Al = 0.8528 gm-atoms

2. Mass Balances and Chemical Equilibrium

In solving this problem on a high-speed digital computer, all products of combustion which could exist would be considered until proven to exist in negligible quantities. However, this rigorous approach is not feasible when using a desk calculator. Therefore, the following species are selected for consideration in this sample calculation: H, Cl, Al(g), CO, CO₂, H₂O, H₂.

HCl, N_2 , AlO, Al_2O , AlCl, $AlCl_3$, $Al_2O_3(s)$, and $Al_2O_3(l)$. Since, in all probability, aluminum oxide will exist in only one condensed phase in the chamber and one condensed phase at the nozzle exit, this propellant system can be solved by 14 simultaneous equations.

The mass balances are:

$$\sum H = 4.2496 = n_H + 2n_{H_2} + 2n_{H_2O} + n_{HCl}$$

$$\sum C = 1.0694 = n_{CO} + n_{CO_2}$$

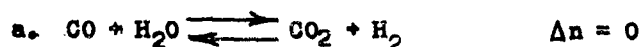
$$\sum N = 0.5277 = 2n_{N_2}$$

$$\sum Cl = 0.5277 = n_{Cl} + n_{HCl} + 3n_{AlCl_3} + n_{AlCl}$$

$$\sum Al = 0.8528 = n_{Al(g)} + n_{AlO} + 2n_{Al_2O} + n_{AlCl} + n_{AlCl_3} + 2n_{Al_2O_3(l)} + 2n_{Al_2O_3(s)}$$

$$\sum O = 2.1107 = n_{CO} + 2n_{CO_2} + n_{H_2O} + n_{AlO} + n_{Al_2O} + 3n_{Al_2O_3(l)} + 3n_{Al_2O_3(s)}$$

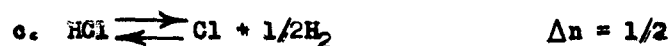
The equations of chemical equilibria may be written as:



$$K_{P1} = \frac{P_{CO_2} \cdot P_{H_2}}{P_{CO} \cdot P_{H_2O}} = \frac{n_{CO_2} \cdot n_{H_2}}{n_{CO} \cdot n_{H_2O}}$$



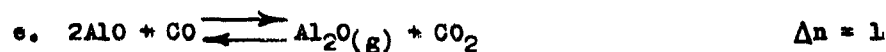
$$K_{P2} = \frac{P_H}{P_{H_2}^{1/2}} = \frac{n_H}{n_{H_2}^{1/2}} \left[\frac{P_T}{n_T} \right]^{1/2}$$



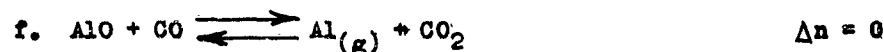
$$K_{P3} = \frac{P_{Cl} \cdot P_{H_2}^{1/2}}{P_{HCl}} = \frac{n_{Cl} \cdot n_{H_2}^{1/2}}{n_{HCl}} \left[\frac{P_T}{n_T} \right]^{1/2}$$



$$K_{P4} = \frac{P_{\text{AlO}} \cdot P_{\text{CO}_2}^{1/2}}{P_{\text{CO}}^{1/2}} = \frac{n_{\text{AlO}} \cdot n_{\text{CO}_2}^{1/2}}{n_{\text{CO}}^{1/2}} \left[\frac{P_T}{n_T} \right]^1$$



$$K_{P5} = \frac{P_{\text{Al}_2\text{O}} \cdot P_{\text{CO}_2}}{P_{\text{AlO}}^2 \cdot P_{\text{CO}}} = \frac{n_{\text{Al}_2\text{O}} \cdot n_{\text{CO}_2}}{n_{\text{AlO}}^2 \cdot n_{\text{CO}}} \cdot \frac{n_T}{P_T}$$



$$K_{P6} = \frac{P_{\text{Al}} \cdot P_{\text{CO}_2}}{P_{\text{AlO}} \cdot P_{\text{CO}}} = \frac{n_{\text{Al}} \cdot n_{\text{CO}_2}}{n_{\text{AlO}} \cdot n_{\text{CO}}}$$



$$K_{P7} = \frac{P_{\text{AlCl}_3}}{P_{\text{Al}} \cdot P_{\text{Cl}}^3} = \frac{n_{\text{AlCl}_3}}{n_{\text{Al}} \cdot n_{\text{Cl}}^3} \left[\frac{P_T}{n_T} \right]^3$$



$$K_{P8} = \frac{P_{\text{Al}} \cdot P_{\text{Cl}}}{P_{\text{AlCl}}} = \frac{n_{\text{Al}} \cdot n_{\text{Cl}}}{n_{\text{AlCl}}} \cdot \frac{P_T}{n_T}$$

3. Chamber Composition Iteration

At an assumed combustion temperature, the chamber composition is calculated. Although general methods of iteration utilizing general equations of equilibrium and matrix techniques are preferred for use on computers, algebraic routines are faster for desk calculator solutions. Therefore, this illustrative example will be solved using trial-and-error algebraic iteration.

An initial combustion temperature of 3500°K is assumed. At 3500°K, the equilibrium constants for the previously chosen equilibrium reactions are:

$$K_1 = K_W = 0.1248$$

$$K_2 = K_H = 0.5888$$

$$K_3 = K_{HCl} = 0.3937$$

$$K_4 = K_{AlO} = 0.04746$$

$$K_5 = K_{Al_2O} = 0.1722$$

$$K_6 = K_{Al} = 0.01564$$

$$K_7 = K_{AlCl_3} = 1.177$$

$$K_8 = K_{AlCl} = 0.1145$$

An initial estimate of n_T , the total moles of gaseous products, is

$$n_T = 1/2(\sum Cl + \sum H + 2\sum C + \sum Al + \sum N)$$

$$n_T = 4.1483 \text{ moles}$$

Also, the initial estimate of n_{H_2} is

$$n_{H_2} = 0.45 (\sum H - \sum Cl + 3\sum Al - \sum O + \sum C)$$

$$n_{H_2} = 2.3576$$

Then,

$$\frac{n_T}{P_T} = \frac{4.1483 \text{ moles}}{1000 \text{ PSI} \times 1 \text{ atm}/14.7 \text{ PSI}} = 0.061004$$

$$\left[\frac{n_T}{P_T}\right]^{1/2} = 0.2470 \quad \left[\frac{P_T}{n_T}\right]^{1/2} = 4.0486$$

Evaluating H ,

$$n_H = K_2 (n_{H_2})^{1/2} \left(\frac{n_T}{P_T}\right)^{1/2} = (0.5888) (1.5354) (0.2470) = 0.2233$$

Evaluating HCl and Cl ,

$$\sum Cl = 0.5277 = n_{Cl} + n_{HCl} + 3n_{AlCl_3} + n_{AlCl}$$

Initially, assume that all chlorine exists as HCl or Cl.

$$\frac{n_{\text{HCl}}}{n_{\text{Cl}}} = \frac{(n_{\text{H}_2})^{1/2}}{K_3} \left(\frac{p_{\text{T}}}{n_{\text{T}}} \right)^{1/2} = \frac{1.5354}{0.3937} (4.0486) = 15.7892$$

$$n_{\text{Cl}} = \frac{\sum \text{Cl}}{\left(\frac{n_{\text{HCl}}}{n_{\text{Cl}}} + 1 \right)} = \frac{0.5277}{16.7892} = 0.0314$$

$$n_{\text{HCl}} = 0.4963$$

Evaluating H_2O .

$$\sum \text{H} = 4.2496 = n_{\text{H}} + 2n_{\text{H}_2} + 2n_{\text{H}_2\text{O}} + n_{\text{HCl}}$$

$$n_{\text{H}_2\text{O}} = 1/2 (\sum \text{H} - 2n_{\text{H}_2} - n_{\text{H}} - n_{\text{HCl}}) = -0.5926$$

However, it would be physically impossible to have a negative quantity of water present. This means that the original estimates of n_{T} and n_{H_2} , especially the latter, were too large. Assume a 5% smaller n_{T} and a 20% smaller n_{H_2} and re-calculate.

$$\text{Let } n_{\text{T}} = (4.1483) (0.95) = 3.9409 \text{ moles}$$

$$n_{\text{H}_2} = (2.3576) (0.80) = 1.8861 \text{ moles}$$

$$\frac{n_{\text{T}}}{p_{\text{T}}} = \frac{3.9409}{68 \text{ atm}} = 0.057954$$

$$\left[\frac{n_{\text{T}}}{p_{\text{T}}} \right]^{1/2} = 0.24074 \quad \left[\frac{p_{\text{T}}}{n_{\text{T}}} \right]^{1/2} = 4.1538$$

Re-evaluating H.

$$n_{\text{H}} = K_2 (n_{\text{H}_2})^{1/2} \left[\frac{n_{\text{T}}}{p_{\text{T}}} \right]^{1/2} = (0.5888) (1.3734) (0.24074) = 0.1947$$

Re-evaluating HCl and Cl.

$$\frac{n_{\text{HCl}}}{n_{\text{Cl}}} = \frac{n_{\text{H}_2}^{1/2}}{K_3} \left[\frac{p_{\text{T}}}{n_{\text{T}}} \right]^{1/2} = \frac{1.3734}{0.3937} (4.1538) = 14.4903$$

$$n_{\text{Cl}} = \frac{\sum \text{Cl}}{\left(\frac{n_{\text{HCl}}}{n_{\text{Cl}}} + 1 \right)} = \frac{0.5277}{15.4903} = 0.0341$$

$$n_{\text{HCl}} = 0.4936$$

Re-evaluating H_2O ,

$$n_{\text{H}_2\text{O}} = 1/2 (\Sigma \text{H} - 2n_{\text{H}_2} - n_{\text{H}} - n_{\text{HCl}}) = -0.1055$$

Again, this is a physical impossibility. This time n_{H_2} will be assumed 10% smaller than before while n_{T} remains 3.9409 moles.

$$n_{\text{H}_2} = (1.8861) (0.90) = 1.6975 \quad n_{\text{H}_2}^{1/2} = 1.3029$$

Re-evaluating H ,

$$n_{\text{H}} = K_2 (n_{\text{H}_2}^{1/2}) \left(\frac{n_{\text{T}}}{P_{\text{T}}} \right)^{1/2} = (0.5888) (1.3029) (0.24074) = 0.1849$$

Re-evaluating HCl and Cl ,

$$\frac{n_{\text{HCl}}}{n_{\text{Cl}}} = \frac{1.3029}{0.3937} (4.1538) = 13.7464$$

$$n_{\text{Cl}} = \frac{0.5277}{14.7464} = 0.0358 \quad n_{\text{HCl}} = 0.4919$$

Re-evaluating H_2O ,

$$n_{\text{H}_2\text{O}} = 1/2 (\Sigma \text{H} - 2n_{\text{H}_2} - n_{\text{H}} - n_{\text{HCl}}) = 0.0889$$

Since water is now present in realistic quantities, the iteration may be continued to other species.

Evaluating CO and CO_2 ,

$$\frac{n_{\text{CO}_2}}{n_{\text{CO}}} = K_1 \frac{n_{\text{H}_2\text{O}}}{n_{\text{H}_2}} = 0.1248 \frac{0.0889}{1.6975} = 0.0065359$$

$$\frac{n_{\text{CO}_2}}{1.0694 - n_{\text{CO}_2}} = 0.0065359$$

$$n_{\text{CO}_2} = 0.00694 \text{ and } n_{\text{CO}} = 1.0625$$

Evaluating AlO .

$$n_{\text{AlO}} = K_4 \left[\frac{n_{\text{CO}}}{n_{\text{CO}_2}} \right]^{1/2} \left[\frac{n_{\text{T}}}{p_{\text{T}}} \right]^1 = \left[\frac{1.0625}{0.00694} \right]^{1/2} (.04746) (.057954) = 0.03403$$

Evaluating Al_2O .

$$n_{\text{Al}_2\text{O}} = (n_{\text{AlO}})^2 (K_5) \frac{n_{\text{CO}}}{n_{\text{CO}_2}} \cdot \frac{p_{\text{T}}}{n_{\text{T}}} = (.03403)^2 (.1722) (153.10) (17.255) = 0.5269$$

However, this is another physical impossibility since $2n_{\text{Al}_2\text{O}} \geq n_{\text{Al}}$.

The concentrations of AlO and Al_2O are greatly affected by the ratio $\frac{n_{\text{CO}}}{n_{\text{CO}_2}}$.

Therefore, this ratio will be introduced as a third unknown variable to facilitate rapid convergence of the aluminum balance. Next, assume

$$\frac{n_{\text{CO}}}{n_{\text{CO}_2}} = 75. \quad \left[\frac{n_{\text{CO}}}{n_{\text{CO}_2}} \right]^{1/2} = 8.66.$$

Re-evaluating AlO .

$$n_{\text{AlO}} = K_4 \left[\frac{n_{\text{CO}}}{n_{\text{CO}_2}} \right]^{1/2} \left[\frac{n_{\text{T}}}{p_{\text{T}}} \right]^1 = (.04746) (8.66) (.057954) = 0.02382$$

Re-evaluating Al_2O .

$$n_{\text{Al}_2\text{O}} = K_5 (n_{\text{AlO}})^2 \frac{n_{\text{CO}}}{n_{\text{CO}_2}} \cdot \frac{p_{\text{T}}}{n_{\text{T}}} = (.1722) (.02382)^2 (75.0) (17.255) = 0.1264$$

Then, other species are:

$$n_{\text{Al}} = (n_{\text{AlO}}) (K_6) \frac{n_{\text{CO}}}{n_{\text{CO}_2}} = (.02382) (.01564) (75.0) = 0.02794$$

$$n_{\text{AlCl}} = \frac{n_{\text{Al}} \cdot n_{\text{Cl}}}{K_8} \frac{p_{\text{T}}}{n_{\text{T}}} = \frac{(.02794) (.0358)}{0.1145} (17.255) = 0.1507$$

$$n_{\text{AlCl}_3} = (n_{\text{Al}}) (n_{\text{Cl}})^3 (K_7) \left[\frac{p_{\text{T}}}{n_{\text{T}}} \right]^3$$

$$n_{\text{AlCl}_3} = (.02794) (3.58 \times 10^{-2})^3 (1.177) (.17255 \times 10^2)^3 = 0.00775$$

Re-evaluating H_2O , CO , and CO_2 .

$$\frac{n_{H_2}}{n_{H_2O}} = K_1 \frac{n_{CO}}{n_{CO_2}} = (0.1248) (75) = 9.360$$

If $n_{H_2} = 1.6975$, then $n_{H_2O} = 0.1814$.

$$\frac{n_{CO}}{n_{CO_2}} = \frac{n_{CO}}{1.0694 - n_{CO}} = 75$$

$$n_{CO} = 1.0553$$

$$n_{CO_2} = 0.0141$$

Re-evaluating HCl and Cl .

$$n_{HCl} = \Sigma H - 2n_{H_2} - n_H - 2n_{H_2O} = 0.3069$$

$$n_{Cl} = \frac{\Sigma Cl - n_{AlCl} - 3n_{AlCl_3}}{\frac{n_{HCl}}{n_{Cl}} + 1} = \frac{0.35375}{15.4903} = 0.0228$$

The other species are:

$$n_{AlCl} = \frac{n_{Al} \cdot n_{Cl}}{K_8} \cdot \frac{P_T}{n_T} = \frac{(.02794) (.0228)}{0.1145} (17.255) = 0.0960$$

$$n_{AlCl} = 0.0960$$

$$n_{AlCl_3} = (.02794) (2.28 \times 10^{-2})^3 (1.177) (.17255 \times 10^2)^3 = 0.0020$$

$$n_{Al_2O_3(i)} = 1/2 (\Sigma Al - n_{Al(g)} - n_{AlO} - 2n_{Al_2O} - n_{AlCl} - n_{AlCl_3}) = 0.2252$$

Checking by oxygen balance,

$$\Sigma O = n_{CO} + 2n_{CO_2} + n_{H_2O} + n_{AlO} + n_{Al_2O} + 3n_{Al_2O_3(i)}$$

$$\Sigma O = 2.1107 \cong 2.0907$$

Checking by total moles balance,

$$n_T = n_{H_2} + n_H + n_{HCl} + n_{CO} + n_{CO_2} + n_{H_2O} + n_{Cl} + n_{AlO} + n_{Al_2O} + n_{Al} + n_{AlCl_3} + n_{H_2} + n_{AlCl}$$

$$T = 3.9409 \cong 4.0029$$

Checking by chlorine balance,

$$\Sigma Cl = n_{Cl} + n_{HCl} + n_{AlCl} + 3n_{AlCl_3}$$

$$\Sigma Cl = 0.5277 \neq 0.4317$$

None of the preceding three material balances is completely satisfied.

However, it is highly improbable that the correct combustion temperature was guessed. Therefore, an enthalpy balance will be made to determine the degree of error in the assumed combustion temperature. Of course, in a high speed digital computer, new values of n_T , n_{H_2} , n_{CO}/n_{CO_2} would be assumed until the material balances each converged.

4. Enthalpy Balance at 3500°K

Species	n_j	H_{298}^T	$n_j H_j$	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j}$
H_2	1.6975	25.702		0	
H	0.1849	15.906		+52.089	
H_2O	0.1814	36.933		-57.798	
CO	1.0553	26.821		-26.416	
CO_2	0.0141	44.003		-94.052	
HCl	0.3069	26.347		-22.063	
Cl	0.0228	16.359		+28.942	
Al	0.0238	28.400		+16.9	
Al_2O	0.1264	44.080		-39.4	
$Al(g)$	0.0279	15.946		+77.4	
AlCl	0.0960	28.414		-50.0	
$AlCl_3$	0.0020	62.700		-137.7	
$Al_2O_3(l)$	0.2252	131.410		-373.09	
N_2	0.2639	26.605		0	
			136.818		-127.681
			166		

$$-(\sum n_j H_j)_p = \Delta H_R = (\sum n_j \Delta H_{f,j})_p - (\sum n_j \Delta H_{f,j})_r$$

$$-136.818 \stackrel{?}{=} -127.681 + 36.633$$

$$-136.818 \neq -91.048$$

Thus, the enthalpy balance is not satisfied. Since the assumed temperature was too high, a combustion temperature of 3100°K will be assumed.

5. Chamber Composition Iteration at 3100°K

$$K_1 = K_W = 0.1349$$

$$K_2 = K_H = 0.2121$$

$$K_3 = K_{HCl} = 0.1453$$

$$K_4 = K_{AlO} = 3.618 \times 10^{-3}$$

$$K_5 = K_{Al_2O} = 1.241$$

$$K_6 = K_{Al} = 1.441 \times 10^{-2}$$

$$K_7 = K_{AlCl_3} = 336.2$$

$$K_8 = K_{AlCl} = 1.421 \times 10^{-2}$$

$$\text{Assume } n_T = 3.8600 \text{ moles}$$

$$\text{Then, } n_T/p_T = 0.056764$$

$$n_{H_2} = 1.8410 \text{ moles}$$

$$p_T/n_T = 17.6166$$

$$n_{CO}/n_{CO_2} = 220$$

$$(n_T/p_T)^{1/2} = 0.23825$$

$$(p_T/n_T)^{1/2} = 4.1972$$

The chamber composition then becomes:

$$n_{N_2} = 0.2639$$

$$n_{CO} = 1.0646$$

$$n_{CO_2} = 0.0048$$

$$n_H = (K_2) (n_{H_2}^{1/2}) \left[\frac{n_T}{p_T} \right]^{1/2} = (.2121) (1.3568) (.23825) = 0.0686$$

$$\frac{n_{H_2}}{n_{H_2O}} = K_1 \frac{n_{CO}}{n_{CO_2}} = (.1349) (220) = 29.678$$

$$n_{H_2O} = 0.0620$$

$$n_{HCl} = \Sigma Cl - 2n_{H_2} - 2n_{H_2O} - n_H = 0.3750$$

$$\frac{n_{HCl}}{n_{Cl}} = \frac{n_{H_2}^{1/2}}{K_3} \left[\frac{P_T}{n_T} \right]^{1/2} = \frac{(1.3568)}{(.1453)} (4.1972) = 39.193$$

$$n_{Cl} = 0.009578$$

$$n_{AlO} = \left(\frac{n_{CO}}{n_{CO_2}} \right)^{1/2} (K_4) \frac{n_T}{P_T} = (14.8324) (.003618) (.056764) = 0.0030$$

$$n_{Al_2O} = (K_5) (n_{AlO})^2 \frac{n_{CO}}{n_{CO_2}} \cdot \frac{P_T}{n_T} = (1.241) (.003046)^2 (220) (17.6166) = 0.0446$$

$$n_{Al} = (K_6) (n_{AlO}) \frac{n_{CO}}{n_{CO_2}} = (.01441) (.003046) (220) = 0.0097$$

$$n_{AlCl} = \frac{(n_{Al}) (n_{Cl})}{K_8} \frac{P_T}{n_T} = \frac{(.009656) (.009578)}{(.01421)} (17.6166) = 0.1147$$

$$n_{AlCl_3} = (K_7) (n_{Al}) (n_{Cl})^3 \left[\frac{P_T}{n_T} \right]^3 = 0.0156$$

$$n_{Al_2O_3(1)} = 1/2 (\Sigma Al - n_{AlO} - 2n_{Al_2O} - n_{Al} - n_{AlCl} - n_{AlCl_3}) = 0.3103$$

Checking oxygen balance.

$$\Sigma O = 2.1107 \cong 2.1147$$

Checking chlorine balance.

$$\Sigma Cl = 0.5277 \cong 0.5461 \quad (\text{Satisfactory checks})$$

Checking total moles balance.

$$n_T = 3.8771 \cong 3.8600$$

6. Enthalpy Balance at 3100°K

Specie	n_j	H_{298}^T	$n_j H_j$	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j298}$
H ₂	1.8410	22.210	40.889	0	0
H	0.0686	13.919	0.955	+52.089	+3.573
H ₂ O	0.0620	31.530	1.955	-57.798	-3.583
CO	1.0646	23.246	24.748	-26.416	-28.122
CO ₂	0.0048	38.021	0.183	-94.052	-0.451
HCl	0.3750	22.756	8.534	-22.063	-8.274
Cl	0.0096	14.529	0.139	+28.942	+0.278
AlO	0.0030	24.726	0.074	+16.9	+0.051
Al ₂ O	0.0446	38.51	1.718	-39.4	-1.757
Al	0.0097	13.957	0.135	+77.4	+0.751
AlCl	0.1147	24.838	2.849	-50.0	-5.735
AlCl ₃	0.0156	54.78	0.855	-137.7	-2.148
Al ₂ O _{3(l)}	0.3103	115.78	35.927	-373.09	-115.780
N ₂	<u>0.2639</u>	23.046	<u>6.082</u>	0	0
	3.8771		125.043		-161.197

$$-(\sum n_j H_j)_p = \Delta H_R = (\sum n_j \Delta H_{f,j298})_p - (\sum n_j \Delta H_{f,j298})_R$$

$$-125.043 \stackrel{?}{=} -161.197 + 36.633$$

$$-125.043 \cong -124.564$$

Thus, the enthalpy balance is satisfied.

7. Calculation of Chamber Entropy and Heat Capacity

Specie	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$	C_p	$n_j C_{p,j}$
H ₂	1.8410	48.761	89.769	0.474	-0.747	-0.354	8.912	16.407
H	0.0686	39.025	2.677	0.018	-4.017	-0.072	4.968	0.341
H ₂ O	0.0620	68.856	4.269	0.016	-4.135	-0.066	13.374	0.829
CO	1.0646	65.662	69.904	0.275	-1.291	-0.355	8.910	9.486
CO ₂	0.0048	80.328	0.386	0.001	-6.908	-0.007	14.902	0.072
HCl	0.3750	62.656	23.446	0.097	-2.333	0.226	8.929	3.348
Cl	0.0096	51.788	0.497	0.002	-6.215	-0.012	5.030	0.048
AlO	0.0030	72.164	0.216	0.001	-6.908	-0.007	9.165	0.027
Al ₂ O	0.0446	96.10	4.286	0.012	-4.423	-0.053	13.90	0.620
Al(g)	0.0097	51.005	0.495	0.002	-6.215	-0.012	4.970	0.048
AlCl	0.1147	74.994	8.602	0.030	-3.507	-0.105	9.086	1.042
AlCl ₃	0.0156	119.40	1.863	0.004	-5.521	-0.022	19.84	0.310
Al ₂ O ₃ (l)	0.3103	92.22	28.616	-----	-----	-----	38.15	11.838
N ₂	<u>0.2639</u>	64.046	<u>16.902</u>	0.068	-2.688	<u>-0.183</u>	8.868	<u>2.310</u>
	3.8771		251.978			-1.474		46.756

$$S_c = \sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln P_c$$

$$S_c = \sum n_j S_j - R n_T \left(\sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln P_c \right)$$

$$S_c = 251.978 - 7.704 (-1.474 + 4.220)$$

$$S_c = 251.978 - 21.155$$

$$S_c = 230.823$$

$$\text{Mean Molecular Weight} = \frac{100 \text{ gm propellant}}{3.8771 \text{ moles of gas}} = 25.79$$

8. Exhaust Composition Iteration

At an assumed exhaust temperature, the exhaust composition is calculated. Assume the exhaust temperature is 2150°K. Since this is below the melting point of Al_2O_3 , the species AlO , Al_2O , Al(g) , and $\text{Al}_2\text{O}_3(\text{l})$ will be neglected in the exhaust composition. Also, the concentrations of Cl and AlCl will be small in comparison to those of HCl and AlCl_3 . Therefore, the following species will be considered: CO , CO_2 , H_2O , H_2 , HCl , H , N_2 , AlCl_3 , and $\text{Al}_2\text{O}_3(\text{s})$. The new mass balances become:

$$\Sigma \text{H} = 4.2496 = 2n_{\text{H}_2} + 2n_{\text{H}_2\text{O}} + n_{\text{HCl}} + n_{\text{H}}$$

$$\Sigma \text{C} = 1.0694 = n_{\text{CO}} + n_{\text{CO}_2}$$

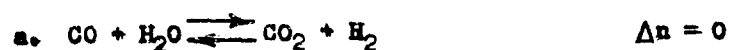
$$\Sigma \text{N} = 0.5277 = 2n_{\text{N}_2}$$

$$\Sigma \text{Cl} = 0.5277 = n_{\text{HCl}} + 3n_{\text{AlCl}_3}$$

$$\Sigma \text{Al} = 0.8528 = 2n_{\text{Al}_2\text{O}_3(\text{s})} + n_{\text{AlCl}_3}$$

$$\Sigma \text{O} = 2.1107 = n_{\text{CO}} + 2n_{\text{CO}_2} + n_{\text{H}_2\text{O}} + 3n_{\text{Al}_2\text{O}_3(\text{s})}$$

Necessary equilibria are:



$$K_{P1} = \frac{P_{\text{CO}_2} \cdot P_{\text{H}_2}}{P_{\text{CO}} \cdot P_{\text{H}_2\text{O}}} = \frac{n_{\text{CO}_2} \cdot n_{\text{H}_2}}{n_{\text{CO}} \cdot n_{\text{H}_2\text{O}}}$$



$$K_{P2} = \frac{P_{\text{H}}}{P_{\text{H}_2}^{1/2}} = \frac{n_{\text{H}}}{n_{\text{H}_2}^{1/2}} \left[\frac{P_{\text{T}}}{n_{\text{T}}} \right]^{1/2}$$

$$K_1 = K_W = 0.19786$$

$$K_2 = K_H = 0.004366$$

$$\text{Assume } n_T = 3.6400 \text{ moles}$$

$$\text{Then, } n_T/P_T = 3.6400$$

$$n_{H_2} = 2.0950 \text{ moles}$$

$$(n_T/P_T)^{1/2} = 1.9079$$

$$n_{CO} = 1.0693$$

$$n_{CO_2} = 0.0001$$

$$n_{N_2} = 0.2639$$

$$\frac{n_{H_2}}{n_{H_2O}} = K_1 \frac{n_{CO}}{n_{CO_2}} = 1978.6$$

$$n_{H_2O} = 0.0011$$

$$n_H = (K_2) (n_{H_2})^{1/2} \left[\frac{n_T}{P_T} \right]^{1/2} = 0.0121$$

$$n_{HCl} = \sum Cl - 2n_{H_2} - 2n_{H_2O} - n_H = 0.0453$$

$$n_{Al_2O_3(s)} = 1/3 (\sum O - n_{CO} - 2n_{CO_2} - n_{H_2O}) = 0.3467$$

$$n_{AlCl_3} = \sum Al - 2n_{Al_2O_3(s)} = 0.1594$$

Checking chlorine balance

$$\sum Cl = 0.5277 \cong 0.5235$$

(Satisfactory Check)

Checking total moles

$$n_T = 3.6462 \cong 3.6400$$

9. Entropy Balance at 2150°K

Constituent	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$
H ₂	2.0950	45.213	94.721	0.576	-0.552	-0.318
H	0.0121	37.206	0.450	0.003	-5.809	-0.017
H ₂ O	0.0011	64.121	0.071	0.000	-----	-----
CO	1.0693	62.434	66.671	0.293	-1.228	-0.360
CO ₂	0.0001	74.939	0.007	0.000	-----	-----
HCl	0.0453	59.446	2.693	0.012	-4.423	-0.053
AlCl ₃	0.1594	112.11	17.870	0.044	-3.124	-0.137
Al ₂ O _{3(s)}	0.3467	67.763	23.493	-----	-----	-----
N ₂	<u>0.2639</u>	60.836	<u>16.055</u>	<u>0.072</u>	-2.631	<u>-0.189</u>
	3.6462		222.121	1.000		-1.074

$$S_e = \sum n_j S_j - R \cdot n_T \left(\sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln P_e \right)$$

$$S_e = 222.121 + (1.074) (7.245)$$

$$S_e = 222.121 + 7.781$$

$$S_e = 229.902$$

$$S_g = 229.902 \cong 230.823 = S_c \quad (\text{Satisfactory check})$$

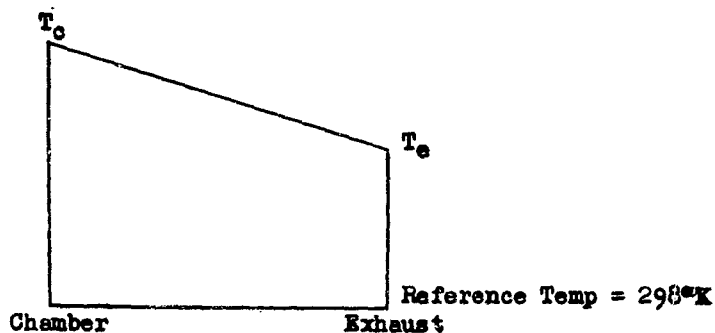
10. Calculation of Exhaust Enthalpy, Heat Capacity, and Heat-of-Formation at 2150°K

Species	n_j	H_{298}^T	$n_j H_j$	C_p	$n_j C_{p_j}$	$\Delta H_{f,298}$	$n_j \Delta H_{f,298}$
H ₂	2.0950	13.896	29.112	8.315	17.420	0	0
H	0.0121	9.200	0.111	4.968	0.060	+52.089	+0.630
H ₂ O	0.0011	19.222	0.021	12.435	0.014	-57.798	-0.064
CO	1.0693	14.866	15.896	8.713	9.317	-26.416	-28.247
CO ₂	0.0001	24.027	0.002	14.518	0.001	-94.052	-0.009
HCl	0.0453	12.710	0.576	8.537	0.387	-22.063	-0.999
AlCl ₃	0.1594	35.93	5.727	19.80	3.156	-137.7	-21.949
Al ₂ O ₃ (s)	0.3467	55.29	19.169	33.80	11.718	-400.4	-138.819
N ₂	<u>0.2639</u>	<u>14.711</u>	<u>3.882</u>	8.653	<u>2.284</u>	0	0
	3.6462		74.496		44.357		-189.457

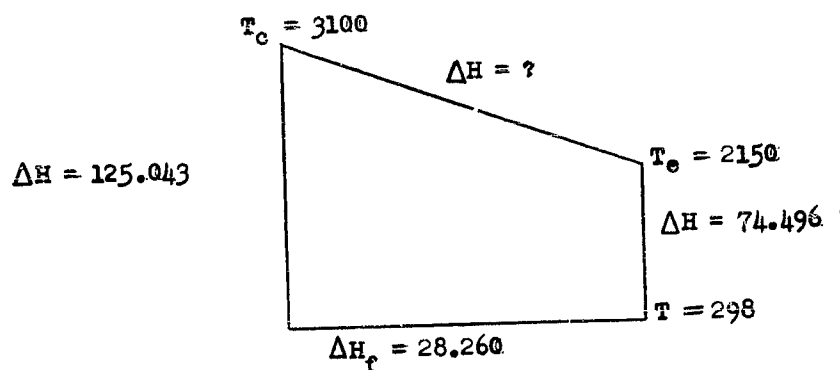
$$\text{Mean Molecular Weight} = \frac{100 \text{ gm propellant}}{3.6462 \text{ moles of gas}} = 27.43$$

11. Overall Enthalpy Balance

Since absolute quantities of enthalpy cannot be assigned, the overall enthalpy balance must be calculated for the complete path followed in the rocket motor:



$$\sum n_j H_{j,298}^{T_e} + \Delta H_{T_c}^{T_e} + \sum n_j H_{j,T_e}^{298} + (\sum n_j \Delta H_{f,j})_e - (\sum n_j \Delta H_{f,j})_c = 0$$



$$125.043 - \Delta H_{T_e}^{T_c} - 74.496 + 28.260 = 0$$

$$\Delta H_{T_e}^{T_c} = 78.807 \text{ Kcal/100 gm}$$

12. Summary of Chamber Conditions

Pressure = 1000 PSIA

Temperature = 3100°K

Enthalpy = 125.043 Kcal/100 gm propellant

Entropy = 230.823 calories/100 gm - °K

Heat Capacity = 46.756 calories /100 gm - °K

Moles of Gas = 3.8771 moles/100 gm

Total Moles = 4.1874 moles/100 gm

Mean Molecular Weight = 25.79 gm/mole

Gas Composition, moles/100 gm propellant

$$H_2 = 1.8410$$

$$H = 0.0686$$

$$H_2O = 0.0620$$

$$CO = 1.0646$$

$$CO_2 = 0.0043$$

$$\text{HCl} = 0.3750$$

$$\text{Cl} = 0.0096$$

$$\text{AlO} = 0.0030$$

$$\text{Al}_2\text{O} = 0.0446$$

$$\text{Al}_{(\text{g})} = 0.0097$$

$$\text{AlCl} = 0.1147$$

$$\text{AlCl}_3 = 0.0156$$

$$\text{Al}_2\text{O}_3(1) = 0.3103$$

$$\text{N}_2 = 0.2639$$

13. Summary of Exhaust Conditions

$$\text{Pressure} = 14.7 \text{ PSIA}$$

$$\text{Temperature} = 2150^\circ\text{K}$$

$$\text{Enthalpy} = 74.496 \text{ Kcal/100 gm propellant}$$

$$\text{Entropy} = 229.902 \text{ calories/100 gm} - ^\circ\text{K}$$

$$\text{Heat Capacity} = 44.357 \text{ calories/100 gm} - ^\circ\text{K}$$

$$\text{Moles of Gas} = 3.6462 \text{ moles/100 gm}$$

$$\text{Total moles} = 3.9929 \text{ moles/100 gm}$$

$$\text{Mean Molecular Weight} = 27.43 \text{ gm/mole}$$

$$\text{Gas Composition, moles/100 gm propellant}$$

$$\text{H}_2 = 2.0950$$

$$\text{H} = 0.0121$$

$$\text{H}_2\text{O} = 0.0011$$

$$\text{CO} = 1.0693$$

$$\text{CO}_2 = 0.0001$$

$$\text{HCl} = 0.0453$$

$$\text{AlCl}_3 = 0.1594$$

$$\text{Al}_2\text{O}_3(s) = 0.3467$$

$$\text{N}_2 = 0.2639$$

14. Calculation of Rocket Performance Parameters

$$a. \text{Isp} = 9.330 \sqrt{H_c - H_e} = 9.330 \sqrt{788.07}$$

$$\text{Isp} = (9.330) (28.071)$$

$$\text{Isp} = 261.9 \text{ seconds}$$

$$b. \text{Ivap} = \rho \cdot \text{Isp} = 1.7715 \frac{\text{gm}}{\text{cc}} \cdot \frac{1 \text{ lb}}{453.6 \text{ gm}} \cdot \frac{1 \text{ cc}}{0.06102 \text{ in.}^3} (261.9 \text{ sec})$$

$$\text{Ivap} = 16.75 \text{ lb-sec/in.}^3$$

$$c. u_e = \text{Isp} \cdot g = (261.9 \text{ seconds}) (32.2 \text{ ft/sec}^2)$$

$$u_e = 8433 \text{ ft/sec}$$

$$d. \frac{k-1}{k} = \frac{\ln \frac{T_c}{T_e}}{\ln \frac{P_c}{P_e}} = \frac{\ln \frac{3100}{2150}}{\ln \frac{68}{1}} = \frac{\ln 1.442}{\ln 68} = 0.0868$$

$$\bar{k} = 1.096$$

$$e. C_F = \sqrt{\frac{4k^2}{k^2-1} \left[\frac{2}{k+1} \right]^{\frac{2}{k-1}} \left[1 - \frac{T_e}{T_c} \right]}$$

$$C_F = \sqrt{(23.44) (0.953)^{20.39} (0.312)} = \sqrt{(7.313) (0.373)}$$

$$C_F = 1.652$$

$$f. \frac{A_e}{A_t} = \frac{k}{C_F} \left[\frac{2}{k+1} \right]^{\frac{k+1}{k-1}} \left[\frac{P_c}{P_e} \right]^{1/k}$$

$$\frac{A_e}{A_t} = \frac{1.096}{1.652} (0.953)^{21.39} (68)^{0.911} = (.665) (.357) (46.7)$$

$$\frac{A_e}{A_t} = 11.09$$

$$g. \quad c^* = \frac{u_e}{C_F} = \frac{8433}{1.652} = 5100$$

$$c^* = 5100 \text{ ft/sec}$$

$$h. \quad \left(\frac{C_p}{C_v} \right)_{\text{chamber}} = k = \frac{C_p}{C_p - n_T \cdot R} = \frac{46.756}{46.756 - (3.8771)(1.987)}$$

$$k = 1.199$$

$$i. \quad \frac{p_e A_e}{\dot{m}} = \frac{1}{a} \cdot n_T \left(\frac{T_e}{I_{sp}} \right)_{\text{shifting}} = \frac{1}{1.15667} (3.6462) \frac{2150}{261.9}$$

$$\frac{p_e A_e}{\dot{m}} = 25.9$$

$$j. \quad g/c^* = a^{1/2} \left[\frac{k}{n_T T_c} \right]^{1/2} \left[\frac{2}{k+1} \right]^{\frac{k+1}{2(k-1)}}$$

$$g/c^* = 1.074 \left[\frac{1.199}{(3.8771)(3100)} \right]^{1/2} \left[\frac{2}{2.199} \right]^{\frac{2.199}{0.398}}$$

$$g/c^* = (1.074)(0.01)(0.587) = 0.00631$$

$$c^* = \frac{g}{0.00631} = 5100 \text{ ft/sec}$$

$$k. \quad C_F = \frac{I_{sp} \cdot g}{c^*} = \frac{(261.9)(32.2)}{5100}$$

$$C_F = 1.655$$

$$l. \quad \frac{A_e}{A^*} = \frac{g}{c^*} \cdot \frac{p_c}{p_e} \cdot \frac{p_e A_e}{\dot{m}} = \frac{32.2}{5100} \cdot \frac{1000}{14.7} (25.9)$$

$$\frac{A_e}{A^*} = 11.12$$

m. Ideal boost velocity data are evaluated as follows:

$$V_b = Isp \cdot g \cdot \ln \left[\frac{W_M}{W_M - W_p} \right] = Isp \cdot g \cdot \ln \left[1 + \frac{\rho}{W_f/V_p} \right]$$

W_f = mass of missile hardware

V_p = volume of propellant

ρ = density of propellant

W_M = total mass of missile

W_p = mass of propellant

$\frac{W_p}{W_M}$	$\frac{W_M}{W_M - W_p}$	$\ln \frac{W_M}{W_M - W_p}$	V_b
0.95	20	3.00	25,300
0.90	10	2.30	19,400
0.85	6.67	1.90	16,020
0.80	5.0	1.61	13,580
0.70	3.33	1.20	10,110
0.50	2.0	0.69	5,820

$\frac{W_f}{V_p}$	$\frac{\rho}{W_f/V_p}$	$1 + \frac{\rho}{W_f/V_p}$	$\ln \left[1 + \frac{\rho}{W_f/V_p} \right]$	V_b
25	4.422	5.422	1.690	14,250
60	1.842	2.842	1.040	8,770
100	1.005	2.005	0.693	5,840

APPENDIX B

SAMPLE CALCULATION USING THE METHOD OF MINIMIZATION OF FREE ENERGY

1. Statement of the Problem

Ingredient	Weight %	Moles/100 gm Propellant	MW	ΔH_{f298} Kcal/mole	gm/cc
N_2H_4	58.207	1.8162	32	+12.05	1.004
N_2O_4	41.793	0.4542	92	-5.4	1.43

Chamber Pressure = 500 PSIA

Exhaust Pressure = 14.7 PSIA

Density of Propellant = 1.148 g/cc

Heat-of-Formation of Propellant = +19.44 Kcal/100 gm

Concentration of Ingredients per 100 gm Propellant:

H = 7.2648 gm-atoms

N = 4.5408 gm-atoms

O = 1.8168 gm-atoms

2. Mass Balance

In solving this problem on a high speed digital computer, all products of combustion which could exist would be considered until proven to be present in negligible quantities. However, such a rigorous approach is beyond the scope and feasibility of this sample calculation. In this example, the purpose is solely to demonstrate the calculation method. Therefore, the products-of-combustion will be limited to the following species: H_2 , H_2O , N_2 , H, N, OH, and O. The mass balances are:

$$\Sigma H = 7.2648 = 2n_{H_2} + 2n_{H_2O} + n_{OH} + n_H$$

$$\Sigma N = 4.5408 = 2n_{H_2} + n_H$$

$$\Sigma O = 1.8168 = n_{H_2O} + n_{OH} + n_O$$

3. Initial Conditions

Initially, in a general solution, it is assumed that the only products of combustion are the elemental gas species. At 298°K, the properties of N, H, and O are:

Species	$\frac{C_p}{R}$	$\frac{\Delta H_f}{R}$
N	4.97 cal/deg-mole	+113.0 Kcal/mole
H	4.968 cal/deg-mole	+52.09 Kcal/mole
O	5.24 cal/deg-mole	+59.55 Kcal/mole

From these data, an enthalpy balance is made with ΔT the variable:

$$-\Sigma (n_j H_j)_{\text{products}} = (\Sigma n_j \Delta H_{f,j298})_{\text{products}} - (\Sigma n_j \Delta H_{f,j298})_{\text{reactants}}$$

$$(\Sigma n_j \Delta H_{f,j298})_{\text{reactants}} = (\Sigma n_j \Delta H_{f,j298})_{\text{products}} + (\Sigma n_j C_{p,j298} \Delta T)_{\text{products}}$$

Species	n_j	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j}$	$C_{p,j}$	$n_j C_{p,j}$
N	4.5408	+113.0	+513.0	4.97	22.5
H	7.2648	+52.09	+377.5	4.968	36.1
O	<u>1.8168</u>	+59.55	<u>+108.0</u>	5.24	<u>9.5</u>
	13.6224		+998.5		68.1

$$+19,440 \text{ calories/100 gm} = 998,500 + 68.1 \Delta T$$

$$\Delta T = -14,400^\circ K$$

This, of course, is a hypothetical temperature corresponding to the existence of species N, H, and O at the constant enthalpy of the propellant. Whenever

the hypothetical temperature of the mixture falls below 298°K, thermodynamic data at 298°K are used for the various product species until the trial temperature raises above that value.

Each of the various products of combustion will now be examined, one by one, to determine which specie will cause the greatest reduction in total free energy of the system if introduced as a constituent. Species are examined and introduced one at a time.

4. Formation of N₂

Nitrogen gas is introduced into the system by formation from nitrogen atoms:



$$2\Delta n_{N_2} = -\Delta n_N$$

The formation of N₂ will cause both a temperature and concentration change. At a given temperature, this relationship is

$$-\Delta T = \frac{H_{N_2} - 2 H_N}{\sum n_j C_{Pj}} \Delta n_{N_2}$$

$$\text{or} \quad -\Delta T = k' \Delta n_{N_2}$$

$$\text{where} \quad k' = \frac{H_{N_2} - 2 H_N}{\sum n_j C_{Pj}}$$

When the temperature of the mixture is a hypothetical value below 298°K, k' is considered zero and the above relationship loses significance. However, when the temperature rises above 298°K, the above expression is used to relate ΔT and Δn .

At 298°K, the ideal entropy and free energy of N and N₂ are:

$$S_N^{\circ} = 36.61 \text{ cal/deg-mole}$$

$$S_{N_2}^{\circ} = 45.77 \text{ cal/deg-mole}$$

$$F_N^{\circ} = H - TS^{\circ} = +113.0 - 10.90 = +102.1 \text{ Kcal/mole}$$

$$F_{N_2}^{\circ} = H - TS^{\circ} = 0 - 13.65 = -13.65 \text{ Kcal/mole}$$

For the general case, the approximate quantity of N₂ which should be introduced in order to minimize the free energy of the system is defined by the equation

$$\Delta F \cong A' \Delta n_{N_2} + B' (\Delta n_{N_2})^2 + C' (\Delta n_{N_2})^3$$

$$\text{where } A' = \text{cal/mole} = k' n_N (-S_N^{\circ})_T + k' n_{N_2} (-S_{N_2}^{\circ})_T + k' n_H (-S_H^{\circ})_T + k' n_O (-S_O^{\circ})_T - 2(F_N^{\circ})_T \\ + (F_{N_2}^{\circ})_T - 2RT (1 + \ln n_N) + RT (1 + \ln n_{N_2}) + k' R (n_N \ln n_N) + k' R (n_{N_2} \ln n_{N_2}) \\ + k' R (n_H \ln n_H) + k' R (n_O \ln n_O) - RT (\ln n_T + 1) - RT \ln p_T + k' R n_T \ln p_T / n_T$$

$$B' = \text{cal/(mole)}^2 = \frac{k' R}{n_N} + \frac{k' R}{n_{N_2}} - 2k' (-S_N^{\circ})_T + k' (-S_{N_2}^{\circ})_T - 2k' R (1 + \ln n_N) + k' R \\ (1 + \ln n_{N_2}) - k' R (\ln n_T + 1) - k' R \ln p_T + RT \frac{(n_{T_{\max}} - n_T) + n_{T_{\max}} \ln \frac{n_T}{n_{T_{\max}}}}{(n_{T_{\max}} - n_T)^2}$$

$$C' = \text{cal/(mole)}^3 = \frac{k' R}{n_N} + \frac{k' R}{n_{N_2}} + k' R \frac{(n_{T_{\max}} - n_T) + n_{T_{\max}} \ln \frac{n_T}{n_{T_{\max}}}}{(n_{T_{\max}} - n_T)^2}$$

$$\text{Then, } \Delta n_{N_2} = \frac{-B' + \sqrt{(B')^2 - 3A'C'}}{3C'}$$

However, k' will be zero at first corresponding to the low hypothetical temperature. Under this condition, the general cubic equation reduces to a quadratic. Furthermore, n_{N_2} is initially zero. Some finite value of n_{N_2} must be assigned, however, in order to avoid infinite contributions to the coefficients A' , B' , C' . For the general case, $2/3$ of the maximum allowable concentration is chosen as the initial quantity to be introduced. This value corresponds to the point of tangency at which, on the average, the $y = ax^2 - bx$ curve approximates the $y = x \ln x$ curve. Thus, the coefficients are evaluated as:

$$A' = -2(102,100) + (-13,650) - 2(1.987)(298)(1 + \ln 4.5408) + (1.987)(298)(1 + \ln 1.5136) - (1.987)(298)(\ln 13.6224 + 1) - (1.987)(298)(\ln 34.0)$$

$$A' = -204,200 - 13,650 - 2976 + 837 - 2139 - 2089$$

$$A' = -224,217$$

$$B' = \frac{4(1.987)(298)}{4.5408} + \frac{(1.987)(298)}{1.5136} + (1.987)(298)(-0.5)$$

$$B' = 616.7$$

$$C' = 0$$

In this case,

$$\Delta F^{\ddagger} \leq A' (\Delta n_{N_2}) + B' (\Delta n_{N_2})^2$$

$$\Delta F \leq -224,217 (\Delta n_{N_2}) + 616.7 (\Delta n_{N_2})^2$$

Differentiating and setting the derivative equal to zero,

$$0 = -224,217 + 1233.4 \Delta n_{N_2}$$

$$\Delta n_{N_2} = 181.8$$

However, according to the mass balance limitation, a maximum of 2.2704 moles of N_2 can be formed.

Therefore, since 181.8 exceeds 2.2704, all nitrogen should exist

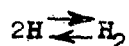
as N_2 . If all N were transformed into N_2 , the total change in ideal free energy of the system at 298°K could be:

$$\Delta F = 2.2704 (-13.65) - 4.5408 (+102.1)$$

$$\Delta F = -494.0 \text{ Kcal}$$

5. Formation of H_2

Consider the introduction of hydrogen gas into the system by formation from hydrogen atoms:



$$2 \Delta n_{H_2} = - \Delta n_H$$

The relationship between temperature and concentration changes is

$$- \Delta T = \frac{n_{H_2} - 2n_H}{\sum n_j C_{p,j}} \Delta n_{N_2}$$

At 298°K, the ideal entropy and free energy of H and H_2 are:

$$S_H^\circ = 27.39 \text{ cal/deg-mole}$$

$$S_{H_2}^\circ = 31.21 \text{ cal/deg-mole}$$

$$F_H^\circ = H - TS^\circ = +52.09 - 8.17 = +43.92 \text{ Kcal/mole}$$

$$F_{H_2}^\circ = H - TS^\circ = 0 - 9.30 = -9.30 \text{ Kcal/mole}$$

Proceeding as before,

$$\Delta' = -2(F_H^\circ)_T + (F_{H_2}^\circ)_T - 2RT (1 + \ln n_H) + RT (1 + \ln n_{H_2}) - RT (\ln n_T + 1)$$

$$- RT \ln p_T$$

$$\Delta' = -103.783$$

$$B' + \frac{4RT}{n_H} + \frac{RT}{n_{H_2}} + RT \frac{(n_{T_{max}} - n_T) + n_{T_{max}} \ln \frac{n_T}{n_{T_{max}}}}{(n_{T_{max}} - n_T)^2}$$

$$B' = 274.4$$

$$C' = a$$

$$\text{Then, } 548.8 \Delta n_{H_2} - 103,783 = a$$

$$\Delta n_{H_2} = 189.1$$

However, according to the mass balance limitations, a maximum of 3.6324 moles of H_2 can be formed. Therefore, since 189.1 exceeds 3.6324, all hydrogen should exist as H_2 in preference to existing as H . For this case, the change in ideal free energy of the system at 298°K would be:

$$\Delta F = 3.6324 (-9.30) - 7.2648 (43.92)$$

$$\Delta F = -352.8 \text{ Kcal}$$

6. Formation of H_2O

Next, consider the formation of water from hydrogen and oxygen:



$$\Delta n_{H_2O} = - \Delta n_O - 2\Delta n_H$$

From the oxygen balance, a maximum of 1.8168 moles of water could be formed.

From the hydrogen balance, a maximum of 3.6324 moles of water could be formed.

Hence, the oxygen balance is the restricting one. The general relationship between ΔT and Δn_{H_2O} is

$$-\Delta T = \frac{n_{H_2O} C_{p_{H_2O}} - 2n_H C_{p_H}}{\sum n_j C_{p_j}} \Delta n_{H_2O}$$

At 298°K, the ideal entropy and free energy of H, O, and H₂O are:

$$S_H^\circ = 27.39 \text{ cal/deg-mole}$$

$$S_O^\circ = 38.47 \text{ cal/deg-mole}$$

$$S_{H_2O}^\circ = 45.11 \text{ cal/deg-mole}$$

$$F_H^\circ = H - TS^\circ = +43.92 \text{ Kcal/mole}$$

$$F_O^\circ = H - TS^\circ = +48.07 \text{ Kcal/mole}$$

$$F_{H_2O}^\circ = H - TS^\circ = -71.21 \text{ Kcal/mole}$$

In this case, the respective constants to the cubic equation are:

$$A' = -2(F_H^\circ)_T - (F_O^\circ)_T + (F_{H_2O}^\circ)_T - 2RT(1 + \ln n_H) - RT(1 + \ln n_O) + RT$$

$$(1 + \ln n_{H_2O}) - RT(\ln n_T + 1) - RT \ln P_T$$

$$A' = -215.119$$

$$B' = \frac{4RT}{n_H} + \frac{RT}{n_O} + \frac{RT}{n_{H_2O}} - RT \frac{(n_{Tmax} - n_T) + n_{Tmax} \ln \frac{n_T}{n_{Tmax}}}{(n_{Tmax} - n_T)^2}$$

$$B' = 844.7$$

$$C' = 0$$

$$\text{Then, } 1689.4 \Delta n_{H_2O} - 215.119 = 0$$

$$\Delta n_{H_2O} = 127.3$$

However, a maximum of 1.8168 moles of water can exist. Since Δn_{H_2O} exceeds this value, all oxygen should exist as water in preference to oxygen atoms.

Furthermore, 3.6324 moles of hydrogen should also be combined. The ideal free energy change accompanying this concentration change is

$$\Delta F = 1.8168(-71.21) - 1.8168(+48.07) - 3.6336(+43.92)$$

$$\Delta F = -375.9 \text{ Kcal}$$

7. Introduction of Major Species

In a general computer solution, all other species, including OH, would be evaluated in the same manner. In fact, the existence of H_2 , N_2 , and H_2O as the predominant species could be reasoned from intuition in this relatively simple example. Nevertheless, the preceding procedure was followed to demonstrate the fundamental approach. Since the greatest single reduction in free energy occurs by transforming N to N_2 , the first new trial composition will be:

$$N_2 = 2.2704 \text{ moles}$$

$$O = 1.8168 \text{ moles}$$

$$H = 7.2648 \text{ moles}$$

Species	n_j	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j}$	$c_{p,j298}$	$n_j c_{p,j}$
N_2	2.2704	0	0	6.96	15.8
H	7.2648	+52.09	+377.5	4.968	36.1
O	1.8168	+59.55	<u>+108.0</u> +485.5	5.24	<u>9.5</u> 61.4

$$19,440 = 485,500 + 61.4 \Delta T$$

$$\Delta T = -7580^\circ K$$

Since the introduction of N_2 was not sufficient to raise the temperature of the mixture to a realistic value, water will also be introduced:

Species	n_j	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j}$	$c_{p,j298}$	$n_j c_{p,j}$
N_2	2.2704	0	0	6.96	15.8
H_2O	1.8168	-57.79	-105.0	8.03	14.6
H	3.6336	+52.09	<u>+189.0</u> +84.0	4.968	<u>18.0</u> 48.4

$$+19,440 = +84,000 + 48.4 \Delta T$$

$$\Delta T = -1330^\circ K$$

Next, let the rest of the H be introduced as H_2 .

Specie	n_j	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j}$	$c_{p,j298}$	$n_j c_{p,j}$
N_2	2.2704	0	0	6.96	15.8
H_2O	1.8168	-57.79	-105.0	8.03	14.6
H_2	<u>1.8168</u> 5.9040	0	<u>0</u> -105.0	6.89	<u>12.5</u> 42.9

$$+19,440 = -105,000 + 42.9 \Delta T$$

$$\Delta T = 2900^\circ K$$

This corresponds to $T_c = 3198^\circ K$. However, the heat capacity data used in obtaining this temperature were extrapolated over a wide range. An enthalpy balance is therefore needed to adjust to the corresponding chamber temperature. At $2700^\circ K$,

$$(\sum n_j \Delta H_{f,j298})_{\text{reactants}} - (\sum n_j \Delta H_{f,j298})_{\text{products}} = -(\sum n_j H_j)_{298 \text{ products}}^T + 124.44 \cong 125.3$$

and the enthalpy balance is essentially satisfied. Actually, by extrapolation $T_c = 2687^\circ K$. The free energy of the system at $2700^\circ K$ is

Specie	n_j	H_j	$n_j H_j$	S_j°	$n_j S_j^\circ$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$	$c_{p,j}$	$n_j c_{p,j}$
N_2	2.2704	+19.52	44.32	62.51	141.9	0.384	-0.957	-0.367	8.80	20.0
H_2O	1.8168	-31.81	-57.79	66.44	120.7	0.308	-1.178	-0.363	12.72	23.1
H_2	<u>1.8168</u> 5.9040	+18.59	<u>33.77</u> +20.30	47.23	<u>85.8</u> 348.4	<u>0.308</u> 1.000	-1.178	<u>-0.363</u> -1.093	8.73	<u>15.9</u> 59.0

$$F = \sum n_j H_j - T \sum n_j S_j + RT n_T \left[\sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} \right] + RT n_T \ln p_T$$

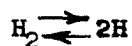
$$F = +20,300 - (2700) (348.4) + (1.987) (2700) (5.9040) (3.526 - 1.093)$$

$$F = +20,300 - 940,080 + 77,065$$

$$F = -842,715 \text{ calories/100 gm propellant}$$

8. Introduction of Minor Species

At 2700°K, some dissociation will be present. Therefore, the species N, H, O, and OH will be re-introduced. First, atomic hydrogen will be considered. Its concentration may be approximated from the decomposition of hydrogen gas by the reaction



$$2 \Delta n_{\text{H}_2} = \Delta n_{\text{H}}$$

$$\Delta n_{\text{T}} = + 1/2 \Delta n_{\text{H}}$$

At constant enthalpy, the formation of H will cause both a temperature and a concentration change. The enthalpy balance becomes

$$\Delta H = 0 = \Delta n_{\text{H}} (H_{\text{H}} - 1/2 H_{\text{H}_2}) + \sum n_j c_{p_j} \Delta T$$

$$-\Delta T = \frac{H_{\text{H}} - 1/2 H_{\text{H}_2}}{\sum n_j c_{p_j}} \Delta n_{\text{H}}$$

$$\text{At } 2700^\circ\text{K}, \quad -\Delta T = \frac{64.02 - 9.30}{59.0} \Delta n_{\text{H}}$$

$$\Delta T = -0.928 \Delta n_{\text{H}}$$

$$S_{\text{H}_2}^\circ = 47.23 \text{ cal/deg-mole}$$

$$S_{\text{H}}^\circ = 38.34 \text{ cal/deg-mole}$$

$$F_{\text{H}_2}^\circ = H - TS^\circ = 18.59 - (2700)(.94723) = -109.6 \text{ Kcal/mole}$$

$$F_{\text{H}}^\circ = H - TS^\circ = 64.02 - (2700)(.03834) = -39.4 \text{ Kcal/mole}$$

Thus, at this point, the species H_2 , N_2 , H_2O , and H are present as products of combustion. The constants for the cubic equation become

$$A' = k' n_{H_2} (-S_{H_2}^0)_T + k' n_H (-S_H^0)_T + k' n_{N_2} (-S_{N_2}^0)_T + k' n_{H_2O} (-S_{H_2O}^0)_T - 1/2 (F_{H_2}^0)_T + (F_H^0)_T - 1/2 RT (1 + \ln n_{H_2}) + RT (1 + \ln n_H) + k'R (n_{H_2} \ln n_{H_2}) + k'R (n_H \ln n_H) + k'R (n_{N_2} \ln n_{N_2}) + k'R (n_{H_2O} \ln n_{H_2O}) - 1/2 RT (\ln n_T + 1) + 1/2 RT \ln p_T + k'R n_T \ln \frac{p_T}{n_T}$$

$$B' = \frac{RT}{4n_{H_2}} + \frac{RT}{n_H} - 1/2 k' (-S_{H_2}^0)_T + k' (-S_H^0)_T - 1/2 k'R (1 + \ln n_{H_2}) + k'R (1 + \ln n_H) - 1/2 k'R (\ln n_T + 1) + RT \frac{(n_T \max - n_T) + n_{T\max} \ln \frac{n_T}{n_{T\max}}}{4(n_{T\max} - n_T)^2}$$

$$+ 1/2 k'R \ln p_T$$

$$C' = \frac{k'R}{4n_{H_2}} + \frac{k'R}{n_H} + \frac{k'R (n_{T\max} - n_T) + n_{T\max} \ln \frac{n_T}{n_{T\max}}}{4(n_{T\max} - n_T)^2}$$

Some finite value of n_H must be initially assigned. Although 2/3 of the maximum allowable concentration would be initially assumed for the general case, the first estimate for this sample problem was made from equilibrium data:

$$n_H = K_p (n_{H_2})^{1/2} \frac{n_T}{p_T}^{1/2} = (0.05669) (1.3440) \frac{5.9040}{34.0}^{1/2} = 0.0316$$

Evaluating the constants,

$$A' = (-0.928) (1.8168) (-47.55) + (-0.928) (0.0316) (-38.34) + (-0.928) (2.2704) (-62.84) + (-0.928) (1.8168) (-66.92) - 1/2 (-109.6) + (-39.4) - 1/2 (1.987) (2700) (1.599) + (1.987) (2700) (-2.45) + (-0.928) (1.987) (1.081) + (-0.928) (1.987) (.109) + (-0.928) (1.987) (1.861) + (-0.928) (1.987) (1.081) - 1/2 (1.987) (2700) (2.775) + 1/2 (1.987) (2700) (3.526) + (-0.928) (1.987) (5.9040) (1.750)$$

$$A' = 80.17 + 1.12 + 132.40 + 112.83 + 54.800 - 39.400 - 4289.2 - 13.143.6$$

$$- 1.99 - 0.2 - 3.43 - 1.99 - 7443.8 + 9.458.3 - 19.05$$

$$A' = + 281.56$$

$$B' = \frac{(1.987)(2700)}{4(1.8168)} + \frac{(1.987)(2700)}{0.0316} - 1/2 (-0.928)(-47.55) + (-0.928)$$

$$(-38.34) - 1/2 (-0.928)(1.987)(1.599) + (0.928)(1.987)(-2.45)$$

$$+ (1.987)(2700) \frac{(13.6224) - 5.9040}{(13.6224 - 5.9040)^2} + 13.6224 \ln \frac{5.9040}{13.6224} + 1/2 (-0.928)$$

$$(1.987)(3.526) - 1/2 (-0.928)(1.987)(2.775)$$

$$B' = 738.23 + 169,773.3 - 21.61 + 35.58 + 1.47 + 4.52 - 2.56 - 82.30 - 3.25$$

$$B' = +170,443.4$$

$$C' = \frac{(-0.928)(1.987)}{4(1.8168)} + \frac{(-0.928)(1.987)}{0.0316} + (-0.928)(1.987)(-0.06137)$$

$$C' = -0.2537 - 58.3525 + 0.0283$$

$$C' = -58.578$$

The change in concentration of hydrogen atoms is evaluated as:

$$\Delta n_H = \frac{-B' + \sqrt{(B')^2 - 3A'C'}}{3C'}$$

$$\Delta n_H = \frac{-170,443.4 + \sqrt{29,051,003,083.23}}{-175.734}$$

$$\Delta n_H = -0.0114 \text{ moles}$$

Thus, the new concentration of H is

$$n_H = 0.0316 - 0.0114 = 0.0202 \text{ moles}$$

By continuing the iteration until all species have been re-introduced and the free energy of the system has been minimized, the gas composition is found to be:

$$n_{N_2} = 2.2704 \text{ moles}$$

$$n_{H_2O} = 1.8112$$

$$n_{H_2} = 1.8051$$

$$n_H = 0.0266$$

$$n_{OH} = 0.0056$$

$$n_O = 0.0000$$

$$n_N = 0.0000$$

9. Enthalpy Balance at 2650°K

Species	n_j	ΔH_{298}^{2650}	$n_j H_j$	$\Delta H_{f,j298}$	$n_j \Delta H_{f,j}$
N_2	2.2704	19.08	43.319	0	0
H_2O	1.8112	25.35	45.914	-57.798	-104.684
H_2	1.8051	18.155	32.772	0	0
H	0.0266	11.68	0.311	+52.089	+1.386
OH	<u>0.0056</u>	18.35	<u>0.103</u>	+ 9.33	<u>+0.052</u>
	5.9189		122.419		-103.246

$$-(\sum n_j H_j)_p = (\sum n_j \Delta H_{f,j298})_F - (\sum n_j \Delta H_{f,j298})_R$$

$$-122.419 = -103.246 - 19.44$$

$$-122.419 \cong -122.686$$

Thus, the enthalpy balance is satisfied at 2650°K.

10. Calculation of Chamber Entropy, Heat Capacity, and Free Energy

Specie	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$	c_p	$n_j c_{p,j}$
N_2	2.2704	62.68	142.31	0.384	-0.947	-0.367	8.79	19.957
H_2O	1.8112	66.68	120.77	0.306	-1.184	-0.362	12.68	22.966
H_2	1.8051	47.29	85.36	0.305	-1.187	-0.362	8.70	15.704
H	0.0266	38.25	1.02	0.004	-5.521	-0.022	4.968	0.132
OH	<u>0.0056</u>	60.28	<u>0.34</u>	<u>0.001</u>	-6.908	<u>-0.007</u>	8.64	<u>0.048</u>
	5.9189		349.80	1.000		-1.120		58.807

$$S_c = \sum n_j S_j - n_T R \sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} - n_T R \ln p_c$$

$$S_c = 349.80 - (5.9189) (1.987) (-1.120) - (5.9189) (1.987) (3.5264)$$

$$S_c = 349.80 + 13.172 - 41.473$$

$$S_c = 321.50 \text{ cal}/(100 \text{ gm}) (^{\circ}\text{K})$$

$$\text{Mean Molecular Weight} = \frac{100 \text{ gm propellant}}{5.9189 \text{ moles of gas}} = 16.895$$

$$F = H - TS$$

$$F = (-103,246 + 122,419) - (2650) (321.50)$$

$$F = +19,173 - 851,975$$

$$F = -832,802 \text{ calories}/100 \text{ gm propellant}$$

Although this free energy is numerically greater than that shown for the system at 2700°K, the enthalpy balance was not completely satisfied at either temperature. Free energy changes become very small as equilibrium is approached. If the exact temperatures were found, the free energy of the dissociated system containing H and OH would be slightly less.

11. Calculation of Exhaust Conditions

During expansion through the nozzle, the minor species H and OH will be converted to H_2 and H_2O so that these, along with N_2 , constitute the exhaust gas composition. This is known for this relatively simple example. However, for solving a general case on a high-speed digital computer, the same method of minimization of free energy previously employed would be utilized at constant entropy. At an exhaust temperature of $1250^\circ K$, the entropy of the system is:

Specie	n_j	S	$n_j S_j$	$\frac{n_j}{n_T}$	$\ln \frac{n_j}{n_T}$	$\frac{n_j}{n_T} \ln \frac{n_j}{n_T}$
N_2	2.2704	56.27	127.801	0.384	-0.957	-0.367
H_2O	1.8168	57.89	105.175	0.308	-1.178	-0.363
H_2	<u>1.8168</u> 5.9040	41.34	<u>75.107</u> 308.083	<u>0.308</u> 1.000	-1.178	<u>-0.363</u> -1.093

$$S_e = \sum n_j S_j - R n_T \left[\sum \frac{n_j}{n_T} \ln \frac{n_j}{n_T} + \ln p_e \right]$$

$$S_e = 308.083 + (1.987) (5.9040) (1.093)$$

$$S_e = 308.083 + 12.822$$

$$S_e = 320.905$$

$$S_e = 320.905 \cong 321.50 = S_c \text{ (Satisfactory Check)}$$

The enthalpy, heat capacity, and free energy are evaluated as:

Specie	n_j	ΔH_{298}^{1250}	$n_j H_j$	$\Delta H_{f,298}$	$n_j \Delta H_{f,298}$	c_p	$n_j c_{p,j}$
N_2	2.2704	7.12	16.165	0	0	8.11	18.413
H_2O	1.8168	8.79	15.970	-57.798	-105.007	10.54	19.149
H_2	<u>1.8168</u> 5.9040	6.78	<u>12.318</u> 44.453	0	<u>0</u> -105.007	7.48	<u>13.590</u> 51.152

$$F = H - TS$$

$$F = (44.453 - 105.007) - (1250) (320.905)$$

$$F = -60,554 - 401,131$$

$$F = -461,685 \text{ calories/100 gm propellant}$$

$$\text{Mean Molecular Weight} = \frac{100 \text{ gm propellant}}{5.9040 \text{ moles of gas}} = 16.95$$

12. Calculation of Rocket Performance Parameters

$$(a) \text{ Isp} = 9.330 \sqrt{H_c - H_g} = 9.330 \sqrt{797.27}$$

$$\text{Isp} = (9.330) (28.236)$$

$$\text{Isp} = 263.0 \text{ seconds}$$

$$(b) \text{ Ivsp} = \rho \cdot \text{Isp} = \frac{(1.148) (263.0)}{(453.6) (.06102)} = 10.90 \text{ lb-sec/in}^3$$

$$(c) u_e = \text{Isp} \cdot g = (263.0) (32.2) = 8465 \text{ ft/sec}$$

$$(d) k = \frac{c_p}{c_p - R n_T} = \frac{58.807}{58.807 - (1.987) (5.9189)} = 1.250$$

$$(e) \frac{P_e A_e}{m} = \frac{1}{a} n_T \left[\frac{T_e}{\text{Isp}} \right]_{\text{shifting}} = \frac{(5.9040) (1250)}{(1.15667) (263)} = 24.35$$

$$(f) g/c^* = a^{1/2} \left[\frac{k}{n_T T_c} \right]^{1/2} \left[\frac{2}{k+1} \right]^{k+1/2}$$

$$g/c^* = (1.074) \left[\frac{1.250}{(5.9189) (2650)} \right]^{1/2} \left[\frac{2}{2.25} \right]^{4.50}$$

$$g/c^* = (1.074) (0.00892) (0.591) = 0.00567$$

$$c^* = \frac{g}{0.00567} = 5680 \text{ ft/sec}$$

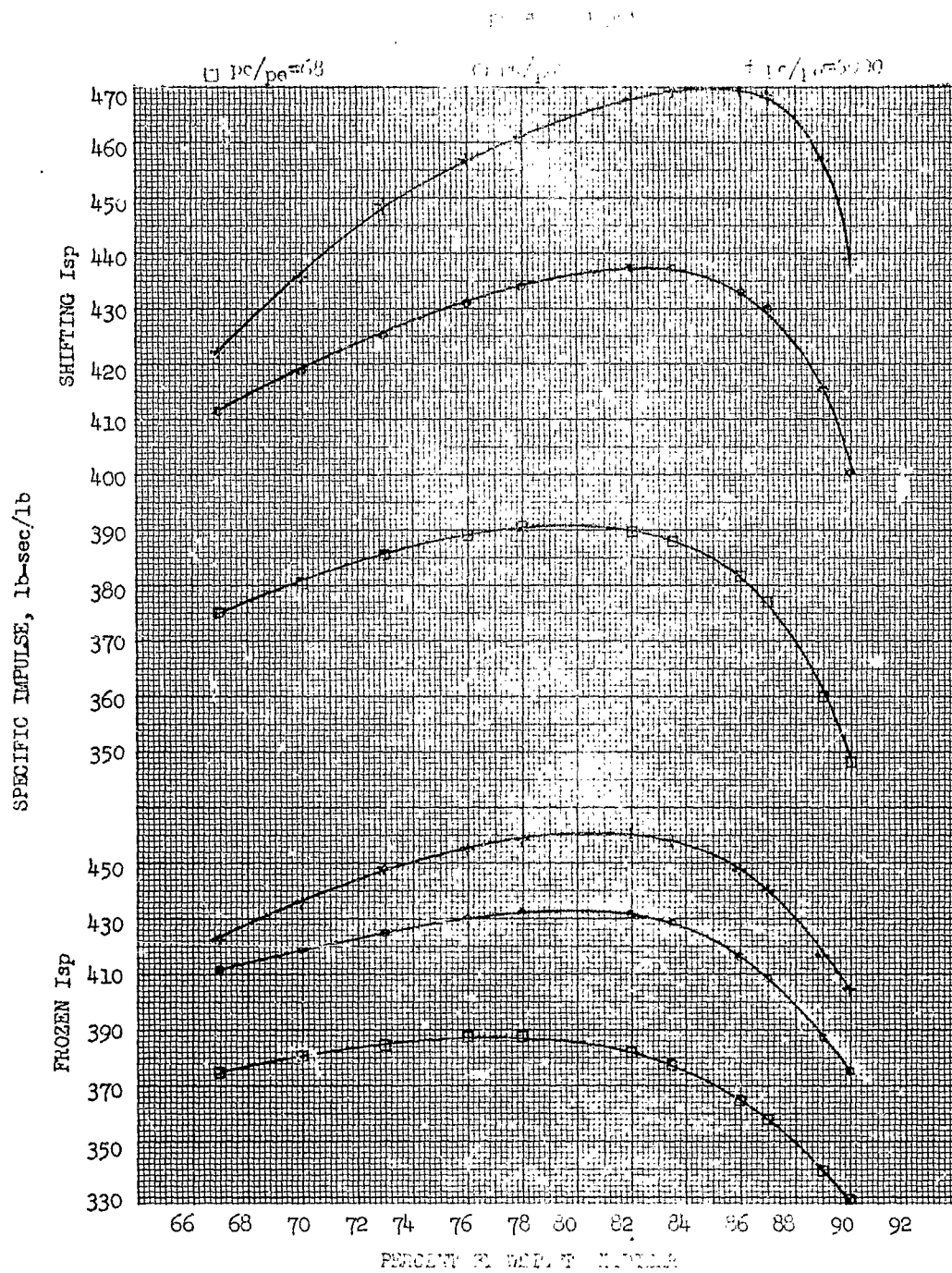
$$(g) c_F = \frac{\text{Isp} \cdot g}{c^*} = \frac{8465}{5680} = 1.491$$

$$(h) \frac{A_e}{A^*} = \frac{g}{c^*} \cdot \frac{P_c}{P_e} \cdot \frac{P_e A_e}{m} = (0.00567) (34.0) (24.25) = 4.69$$

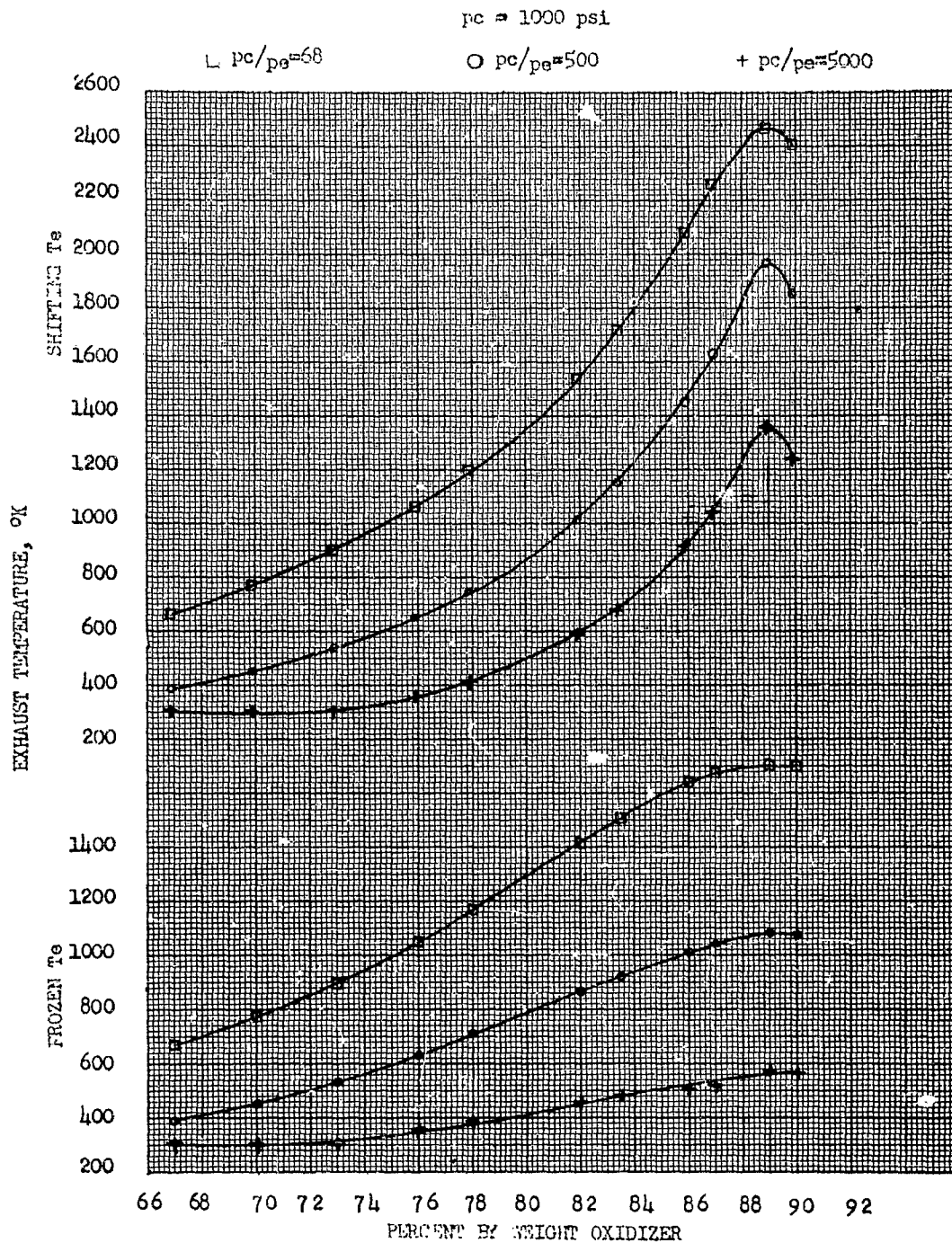
APPENDIX C

Theoretical Performance Curves for the Various Propellant Systems

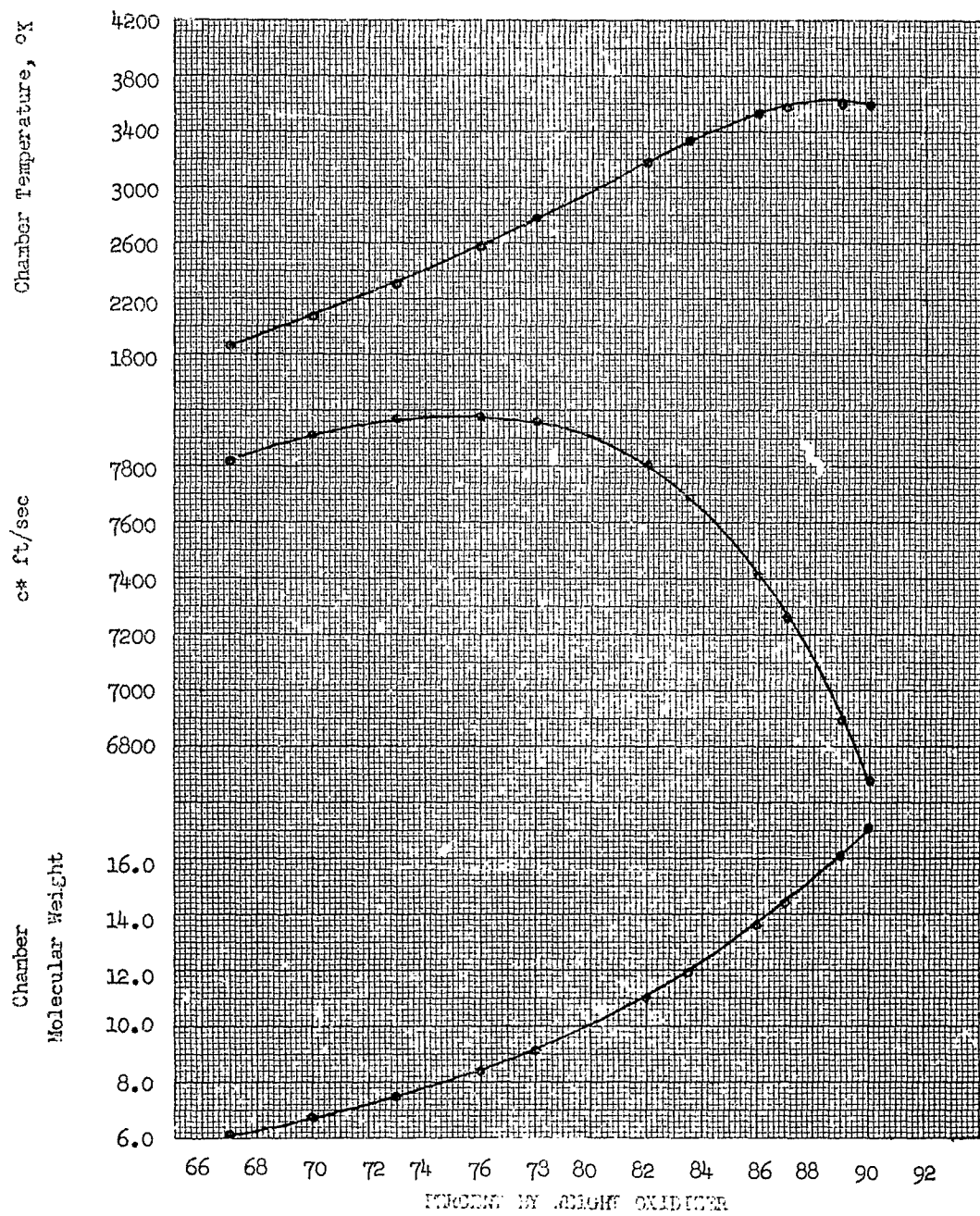
LIQUID HYDROGEN - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 1



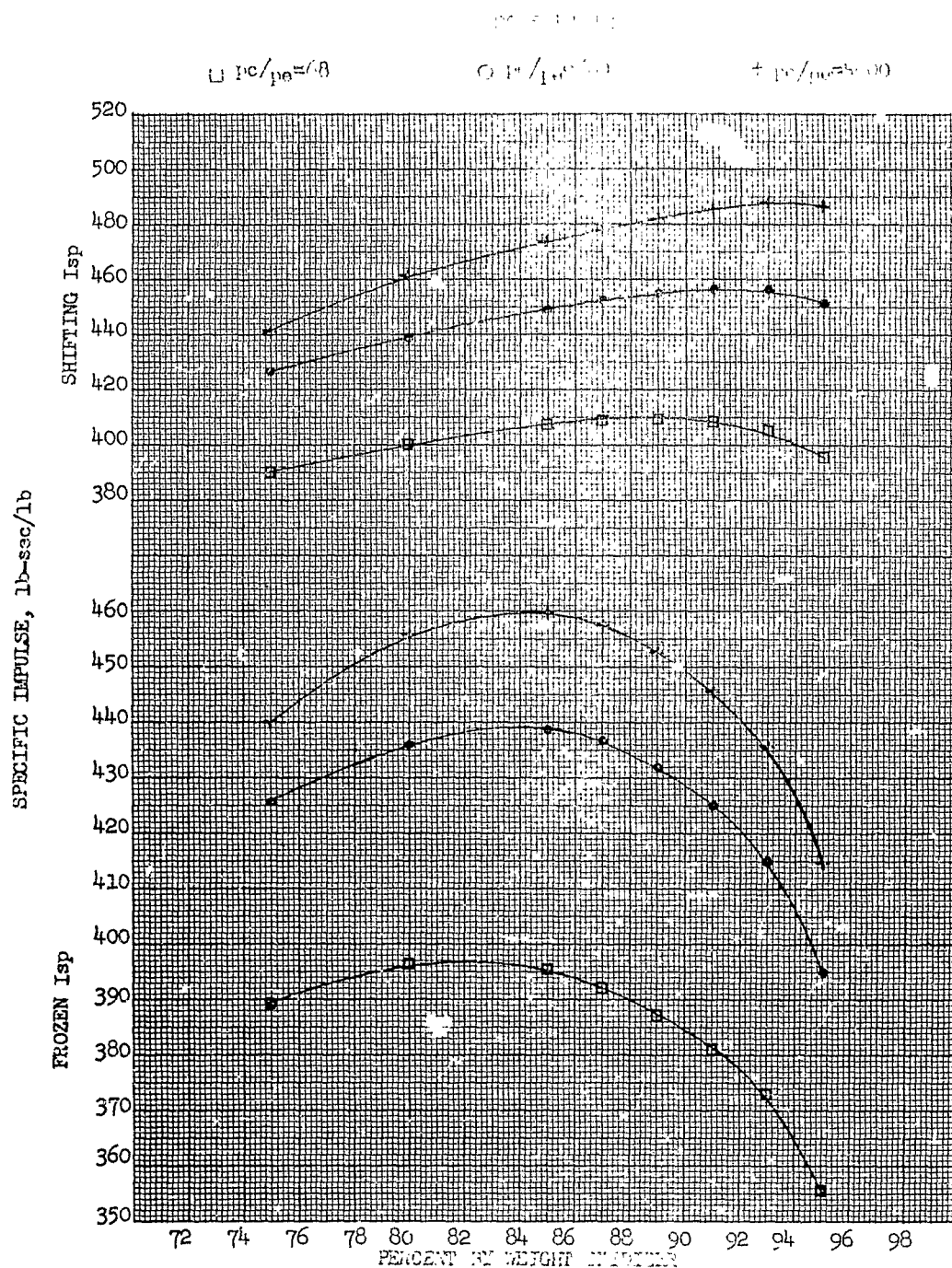
LIQUID HYDROGEN - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 2



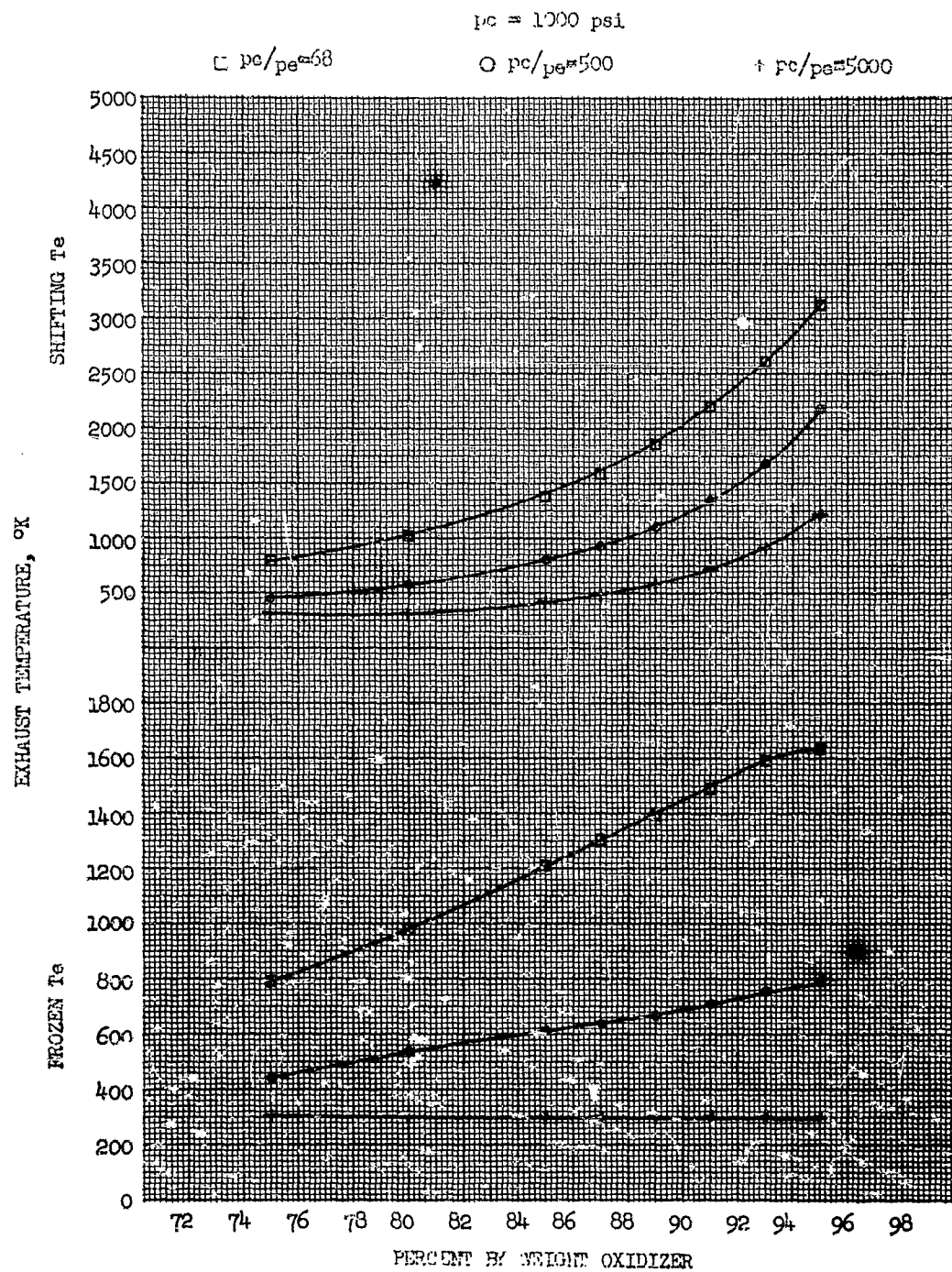
LIQUID HYDROGEN - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 3



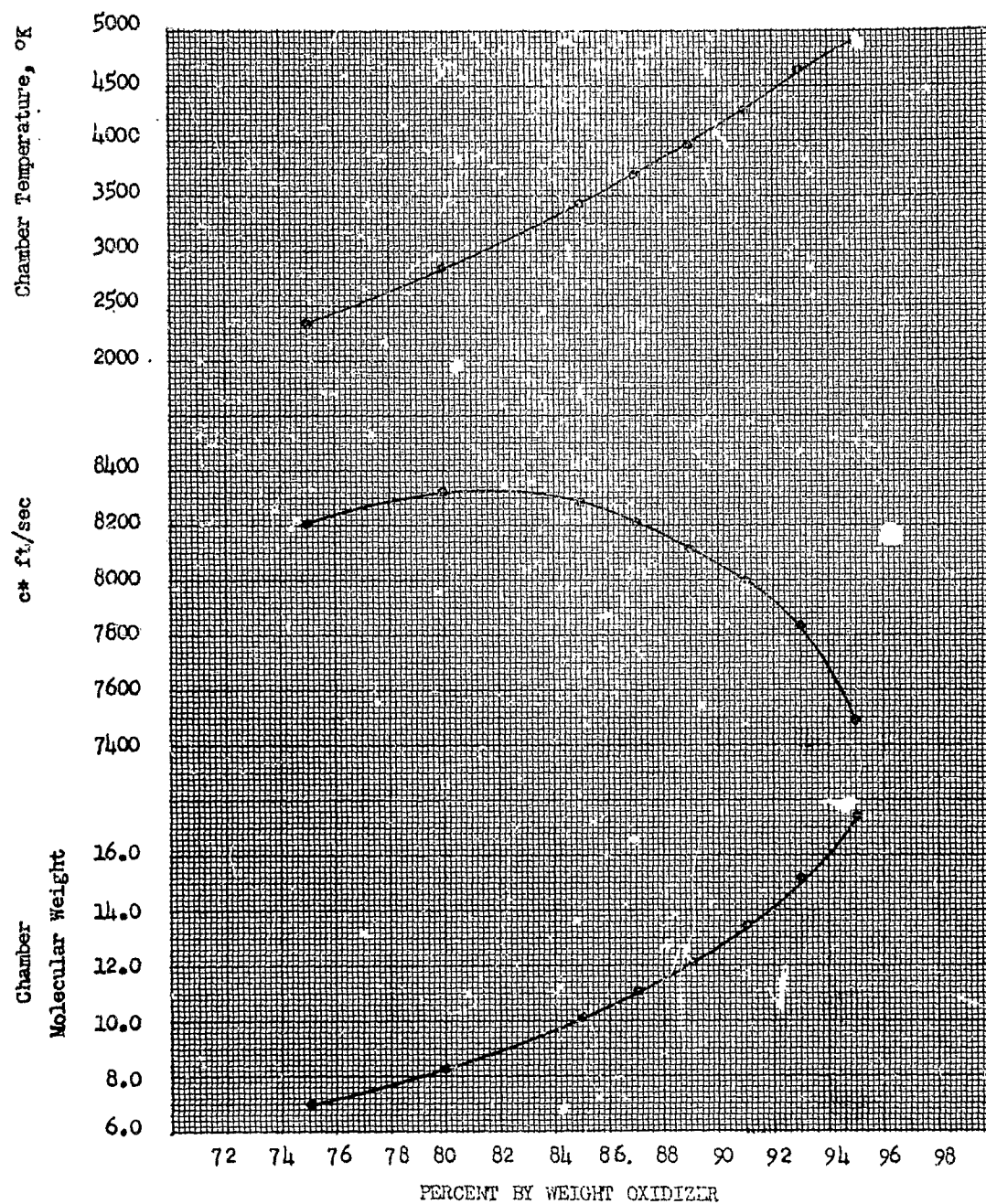
LIQUID HYDROGEN - LIQUID FLUORINE TERFENYL - CURVES FIGURE 4



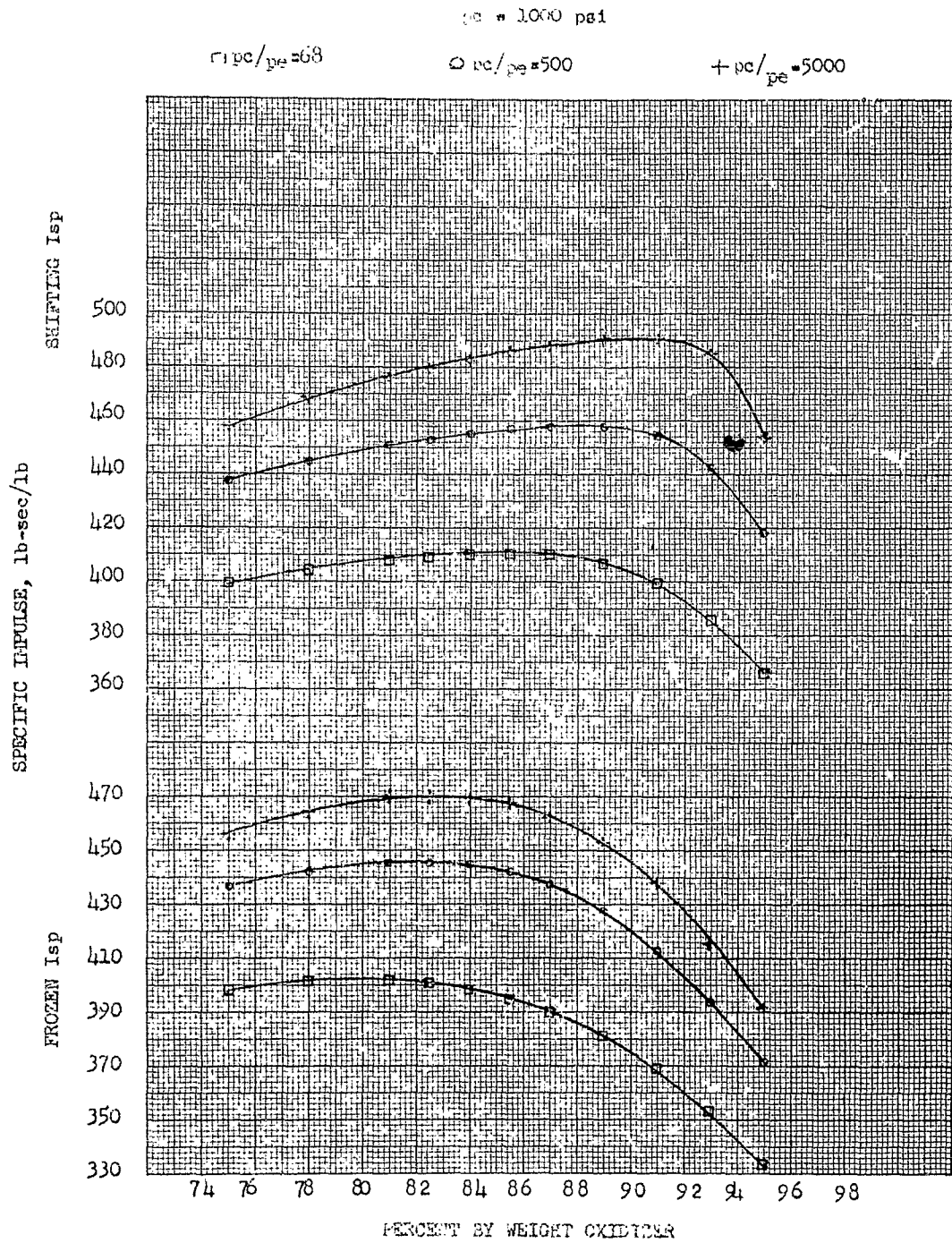
LIQUID HYDROGEN - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 5



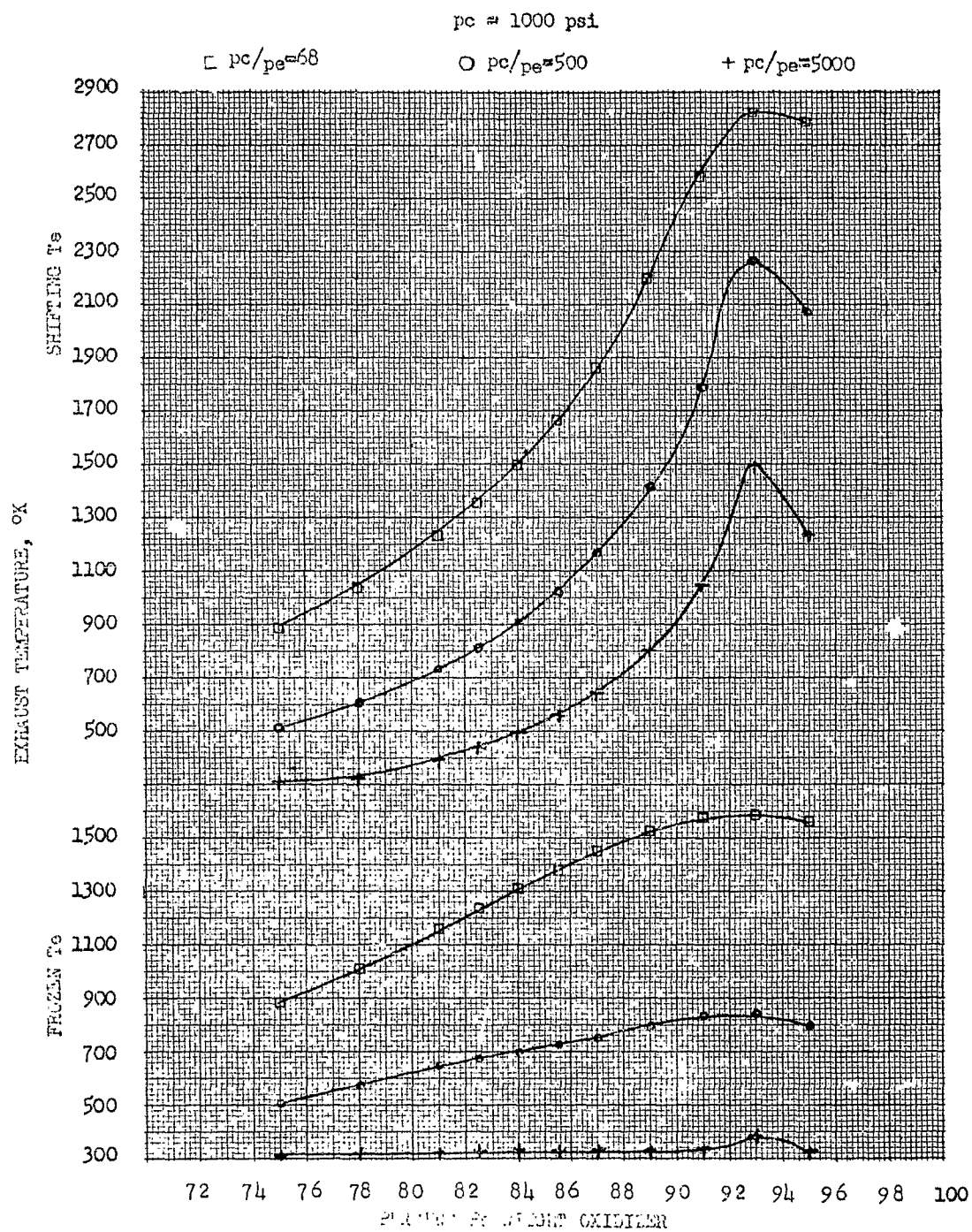
LIQUID HYDROGEN - LIQUID FLUORINE PEROXIDE CURVES FIGURE 6



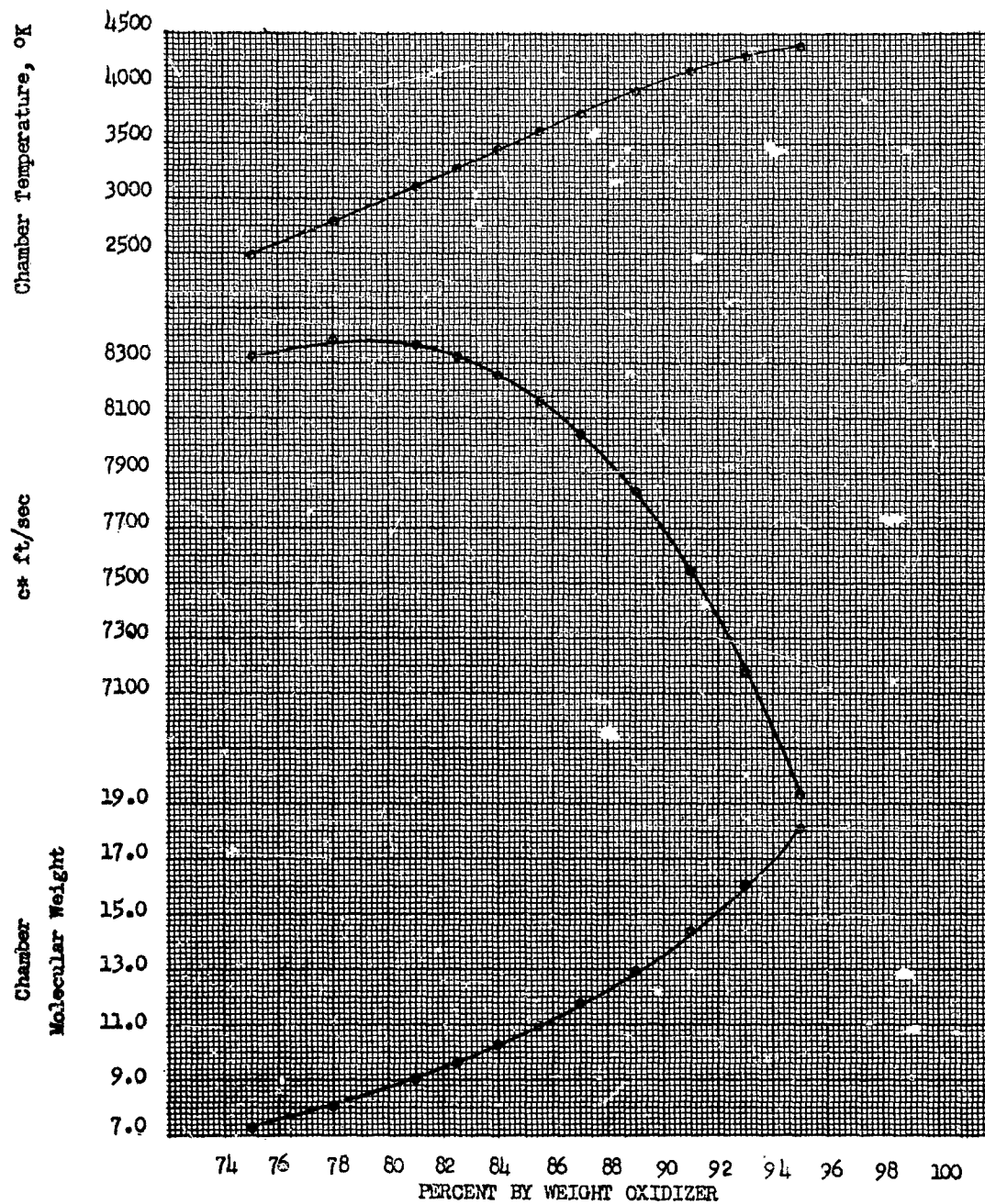
LIQUID HYDROGEN - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 7



LIQUID HYDROGEN - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 8



LIQUID HYDROGEN - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 9



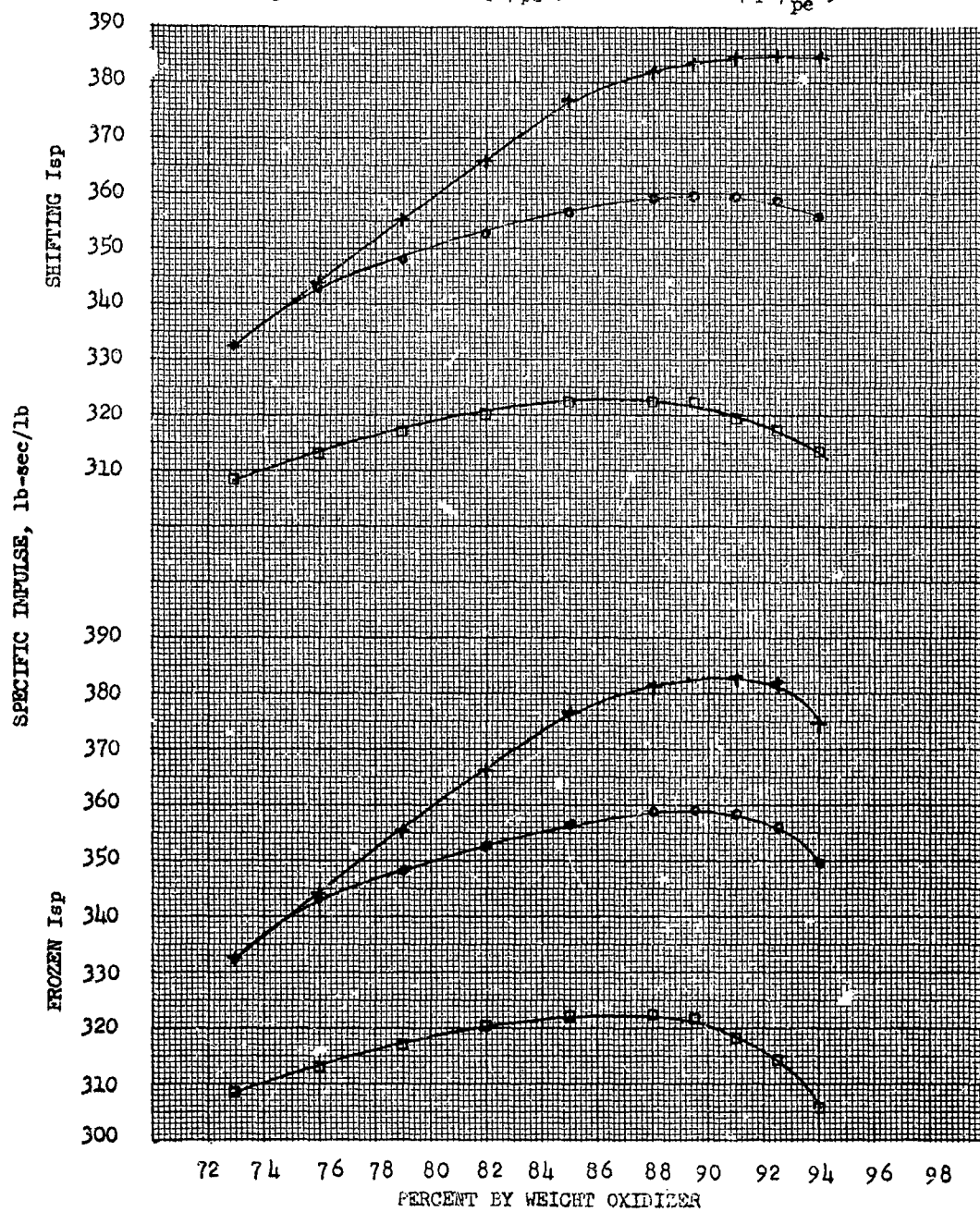
LIQUID HYDROGEN - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 10

pc = 1000 psi

□ pc/pe = 68

○ pc/pe = 500

+ pc/pe = 5000



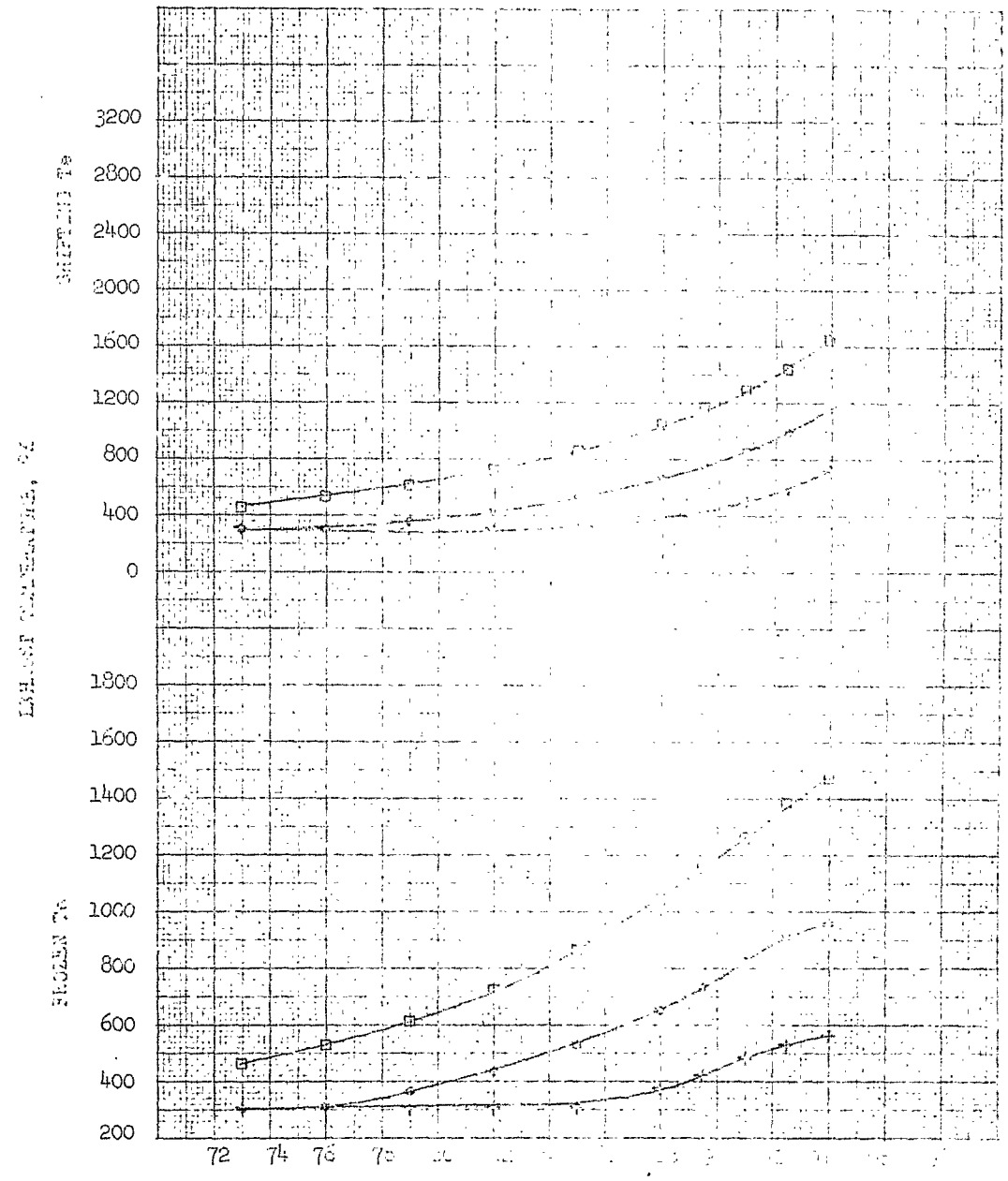
LIQUID HYDROGEN - 10000 PSI

10000 PSI

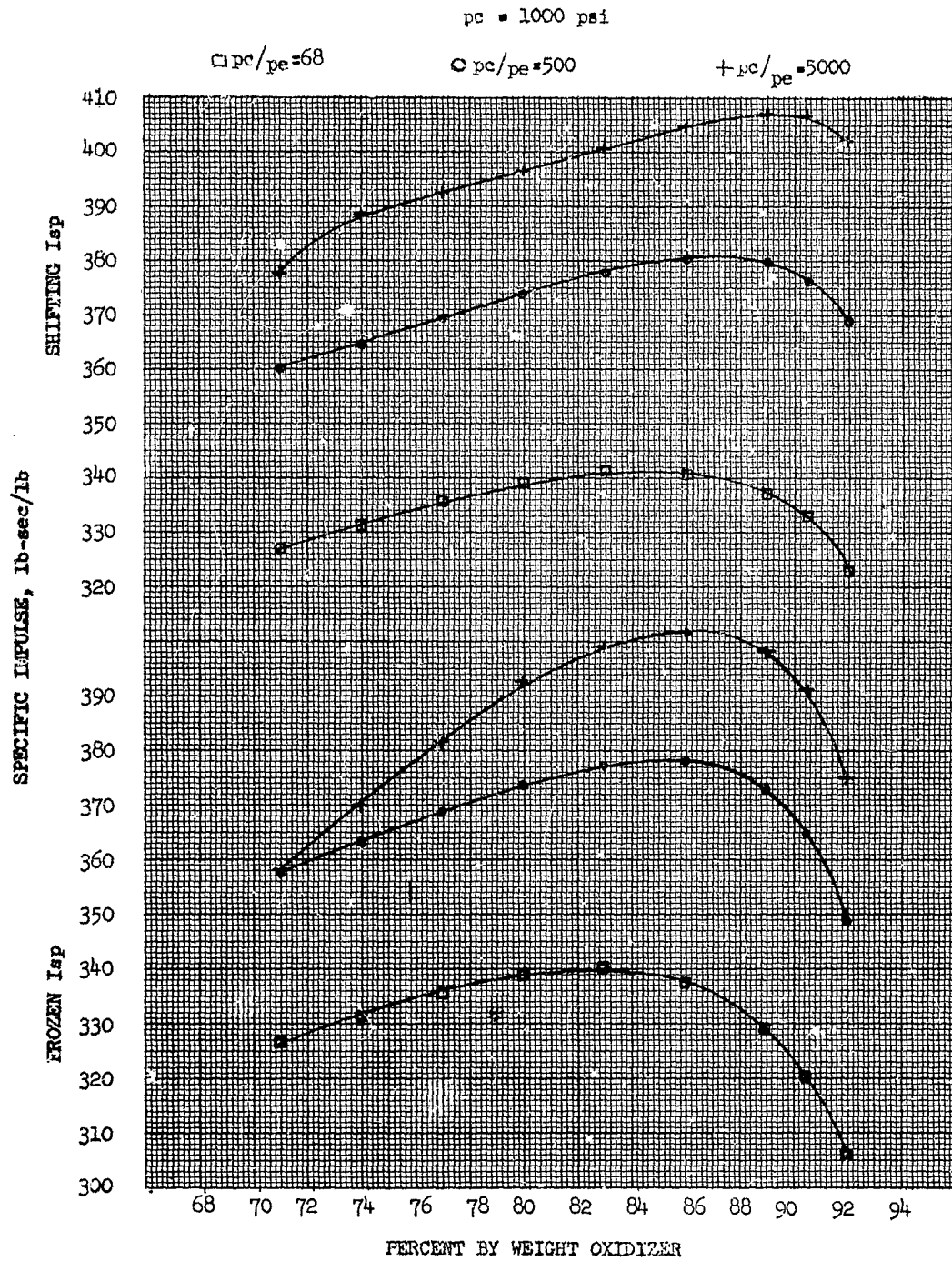
$L/P_0 = 0.5$

$L/P_0 = 0.5$

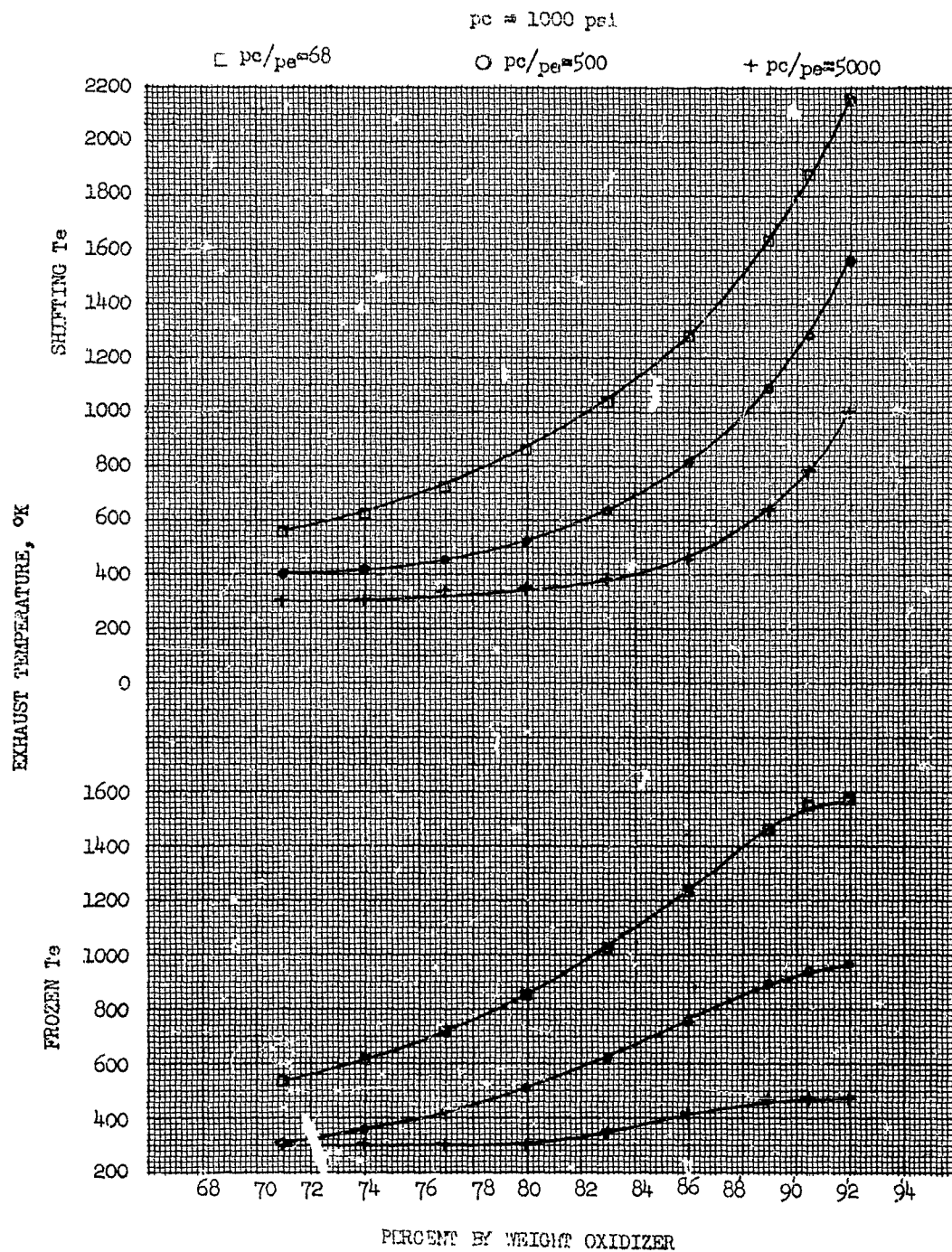
$L/P_0 = 0.5$

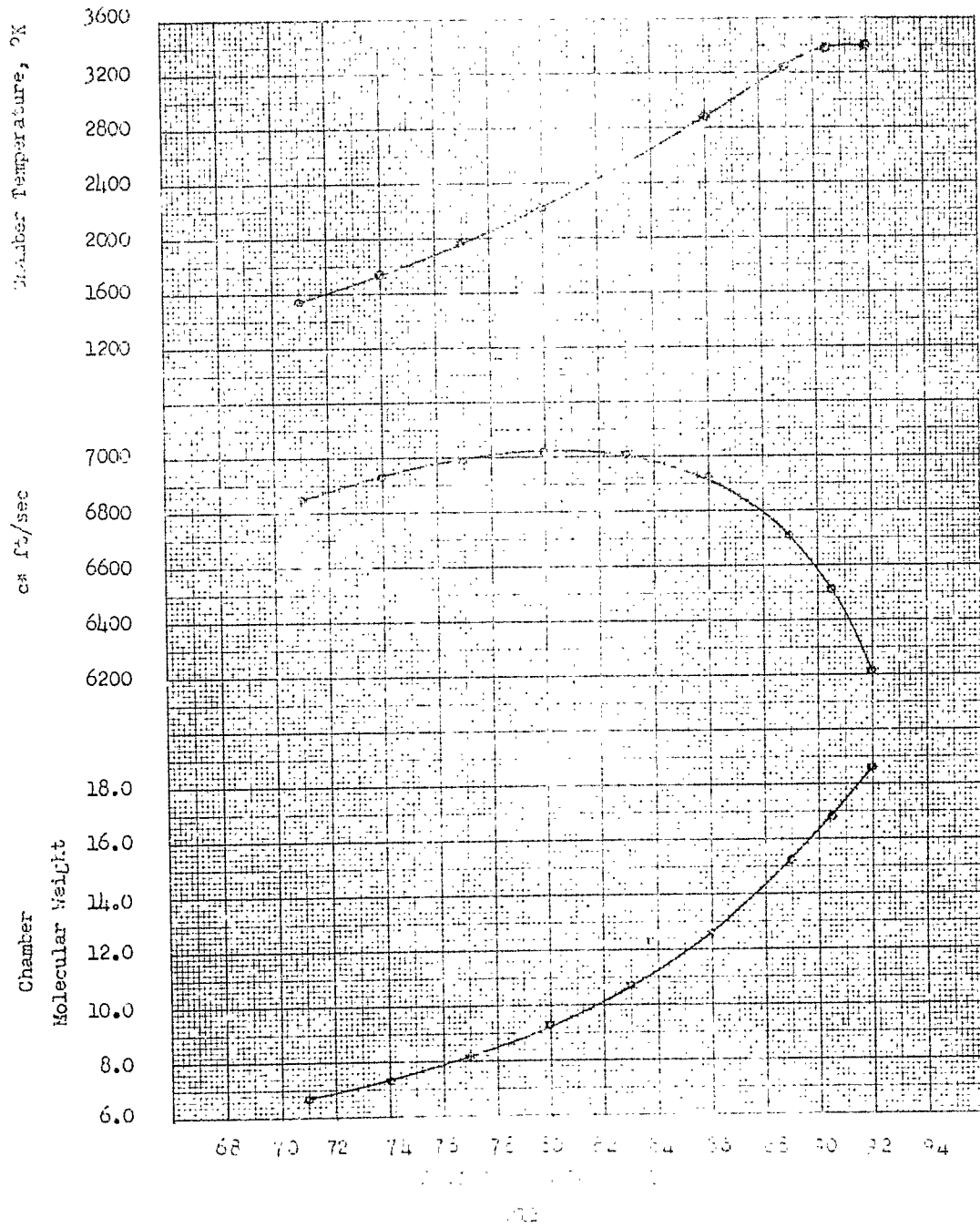


LIQUID HYDROGEN - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 13



LIQUID HYDROGEN - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 14





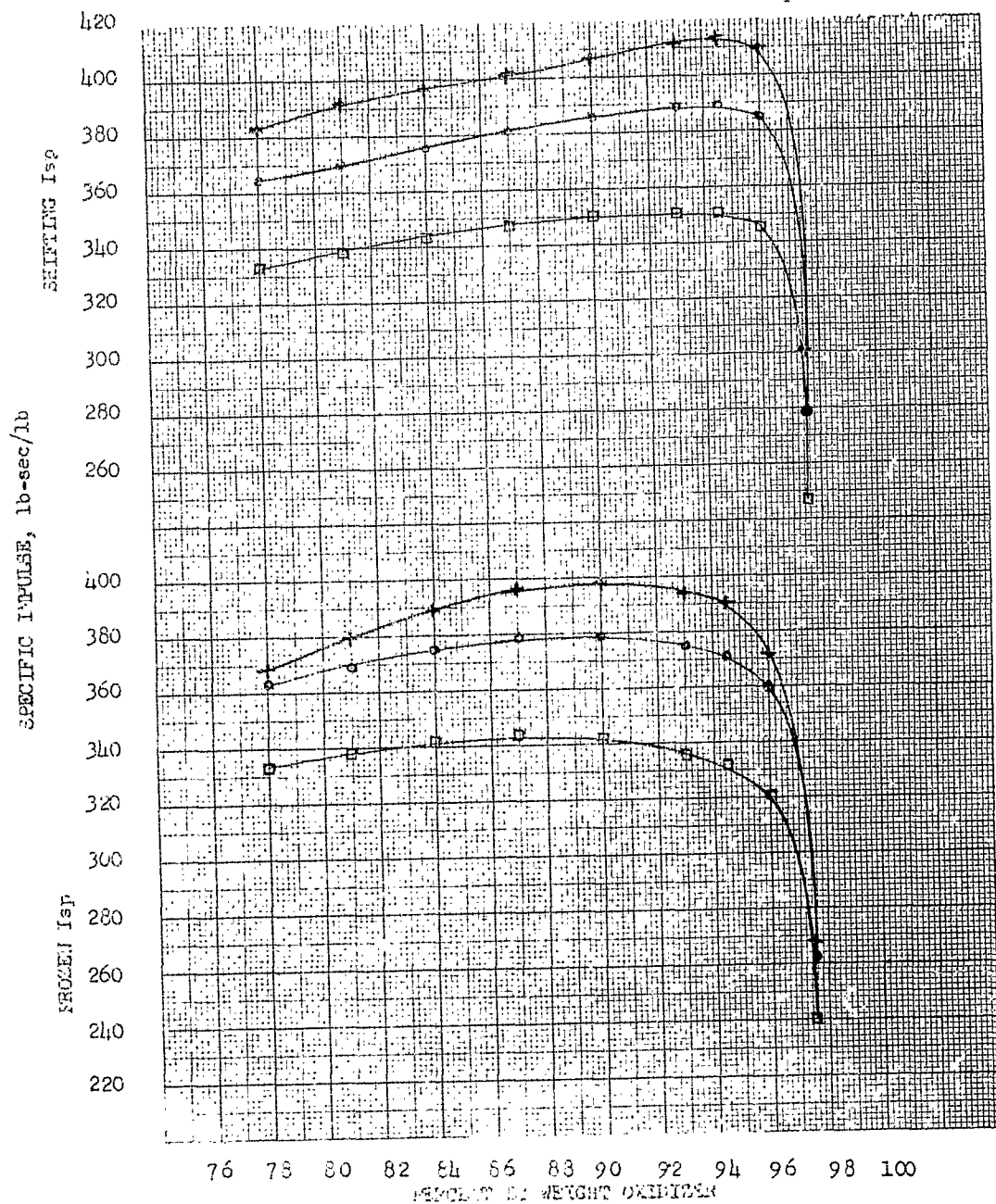
LIQUID HYDROGEN - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 16

$p_c = 1000 \text{ psf}$

$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$



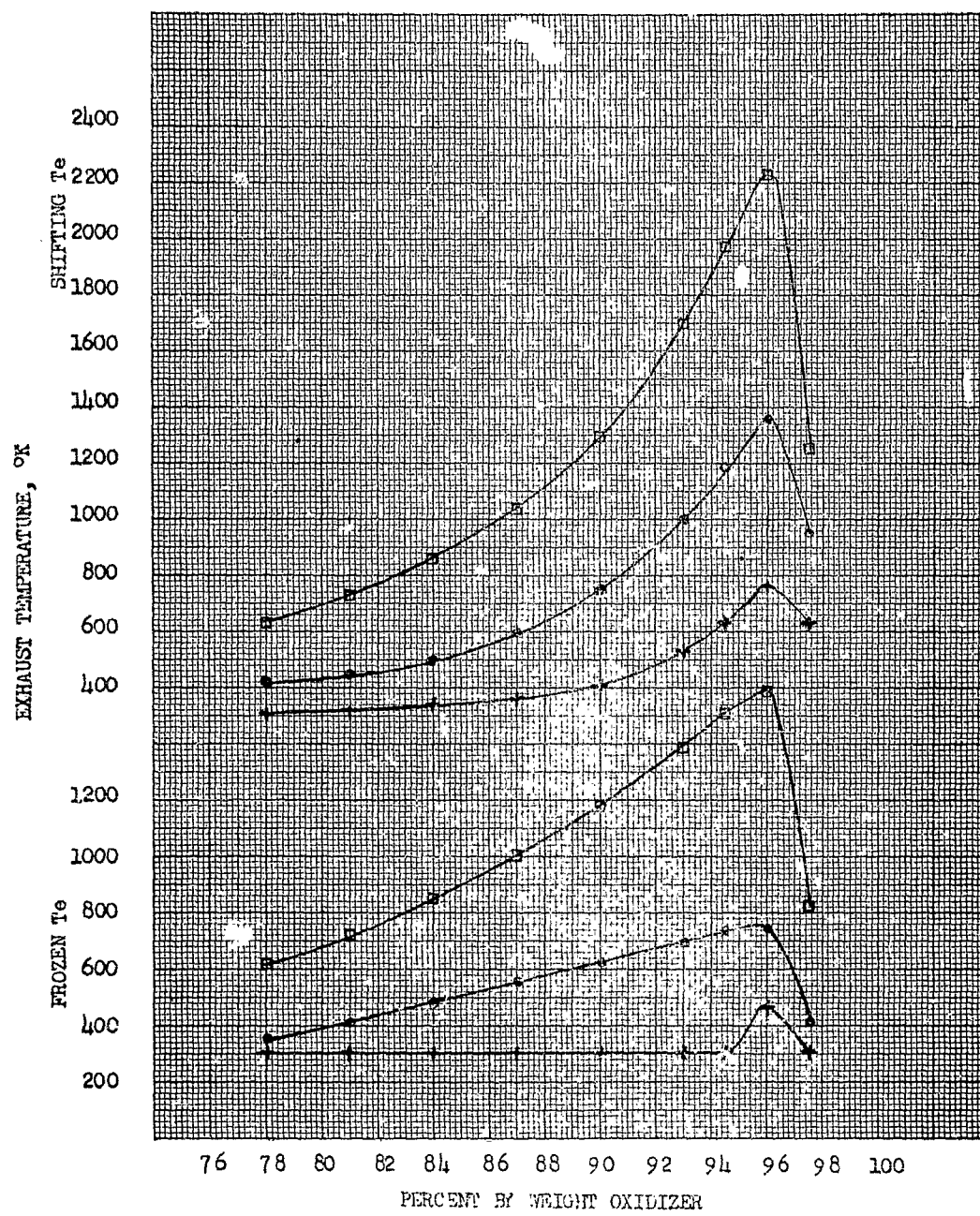
LIQUID HYDROGEN - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 17

$p_c \approx 1000 \text{ psi}$

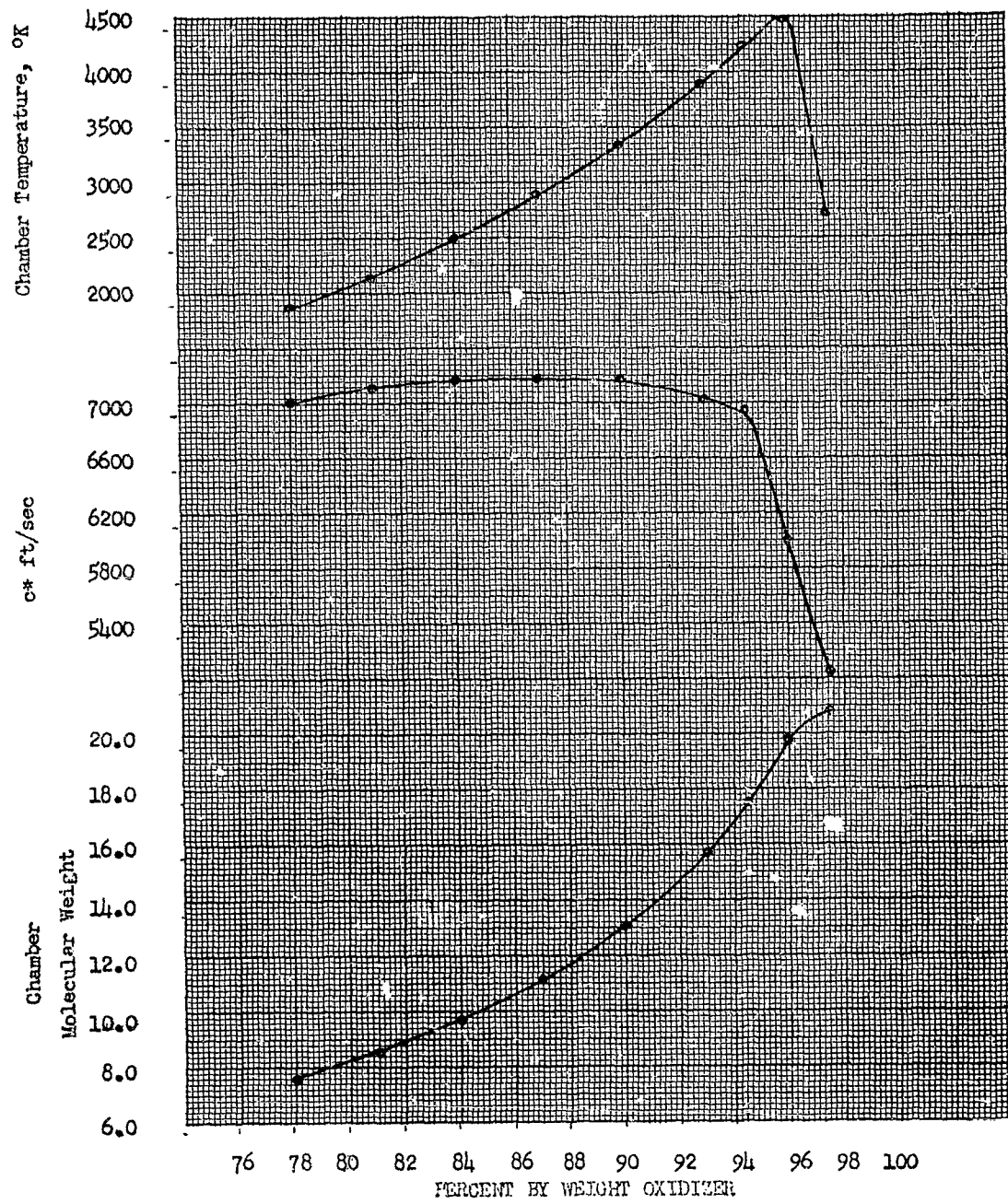
$\square p_c/p_a \approx 68$

$\circ p_c/p_a \approx 500$

$+ p_c/p_a \approx 5000$



LIQUID HYDROGEN - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 18



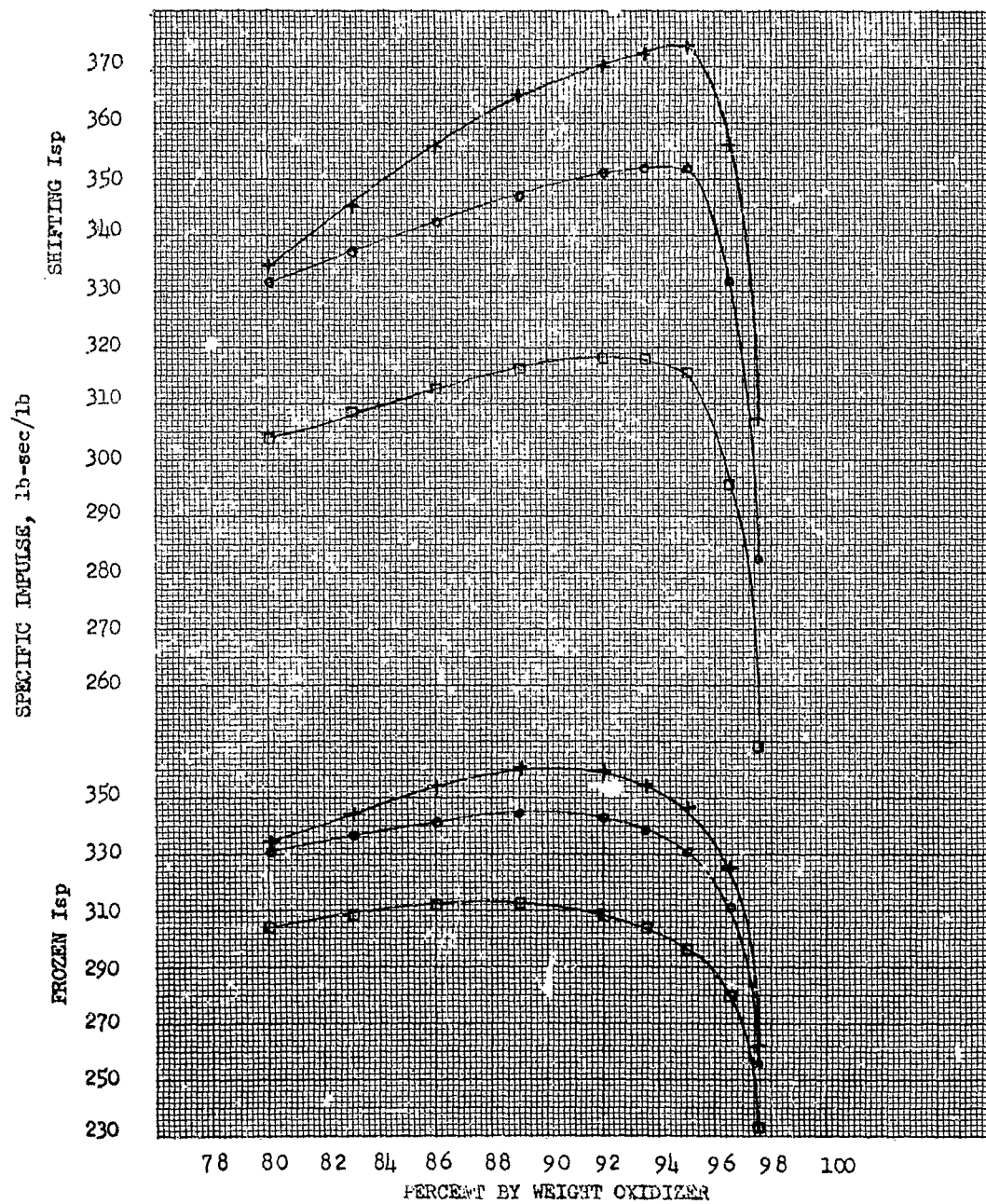
LIQUID HYDROGEN - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 19

$p_c = 1000 \text{ psi}$

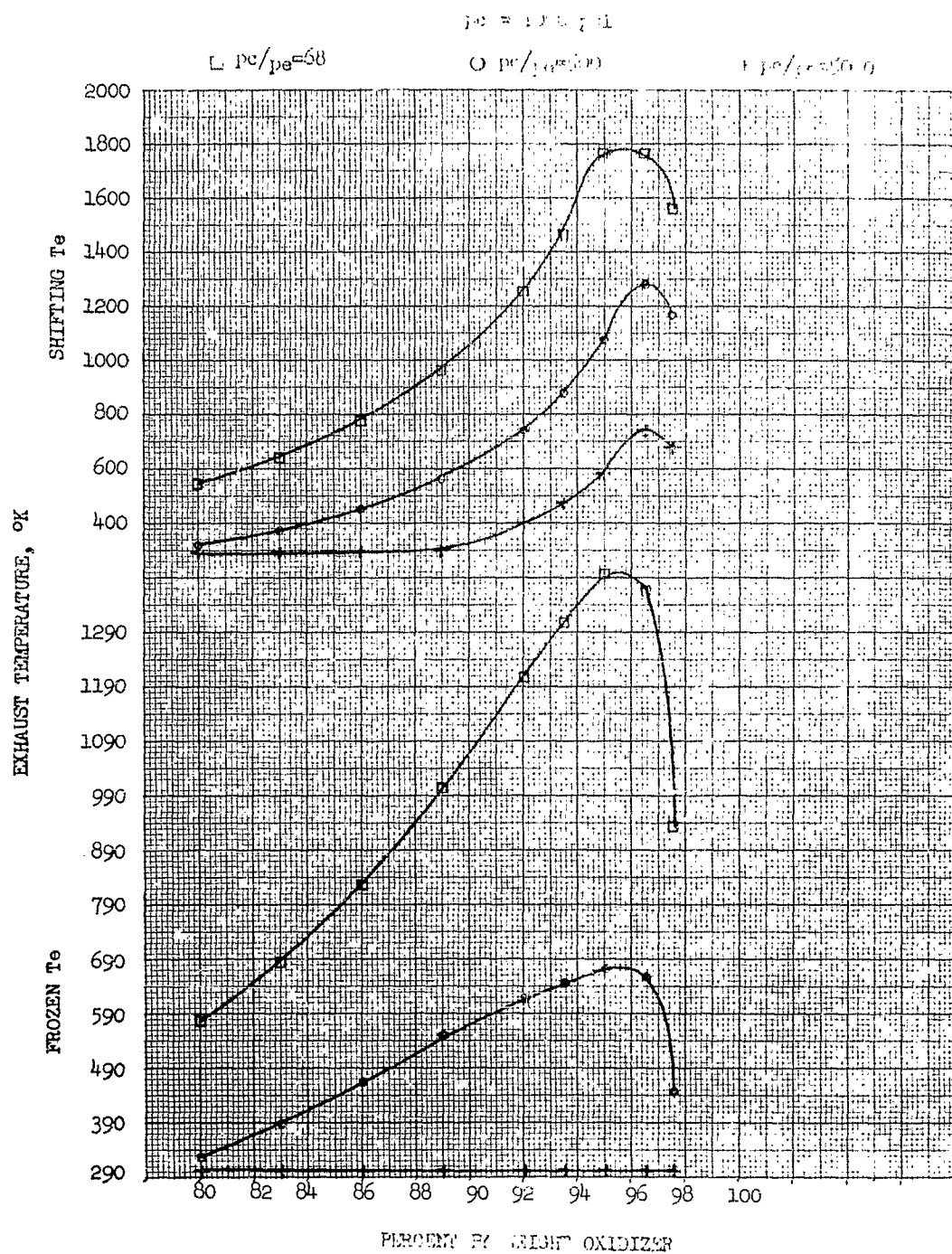
$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

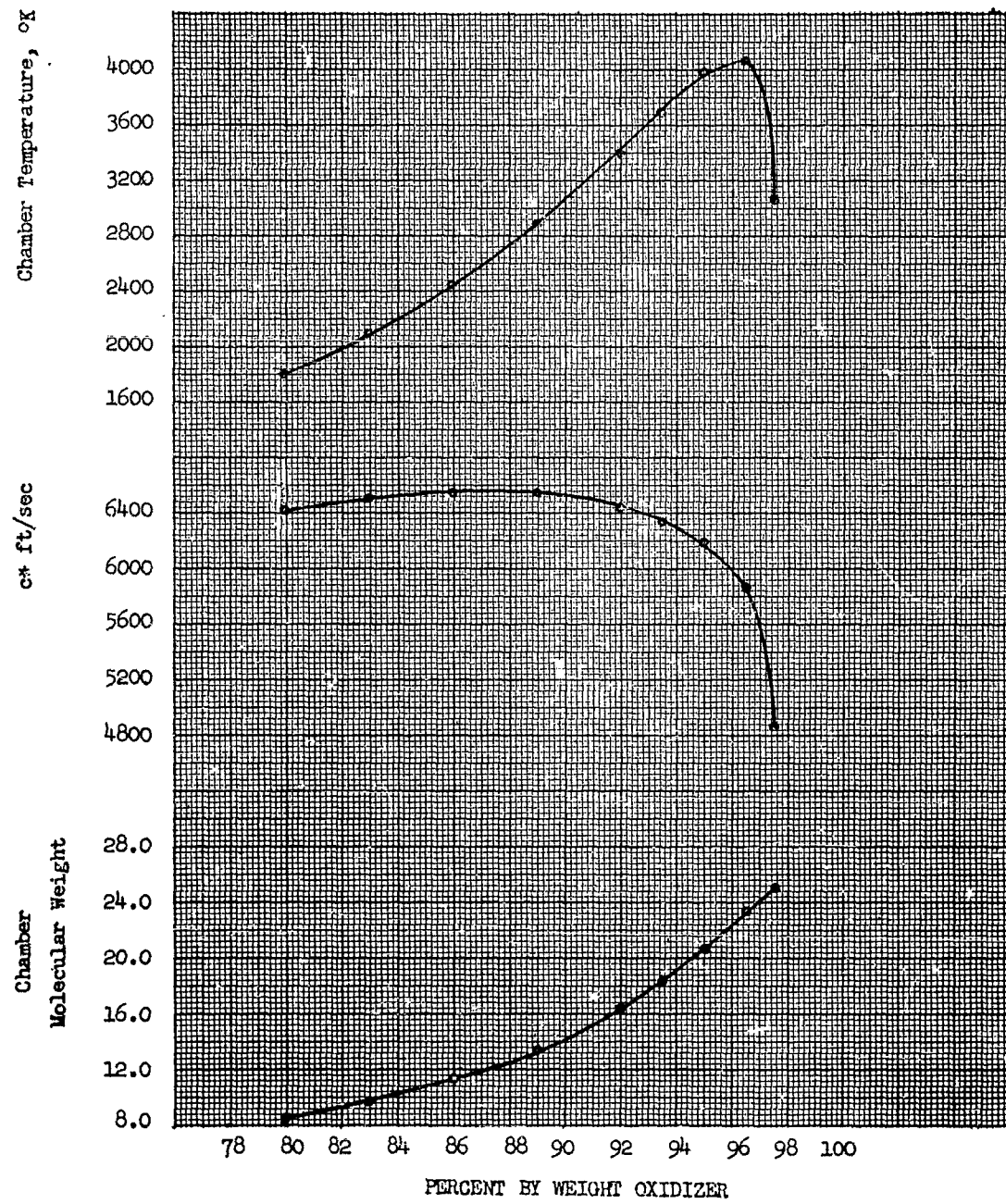
$+ p_c/p_e = 5000$



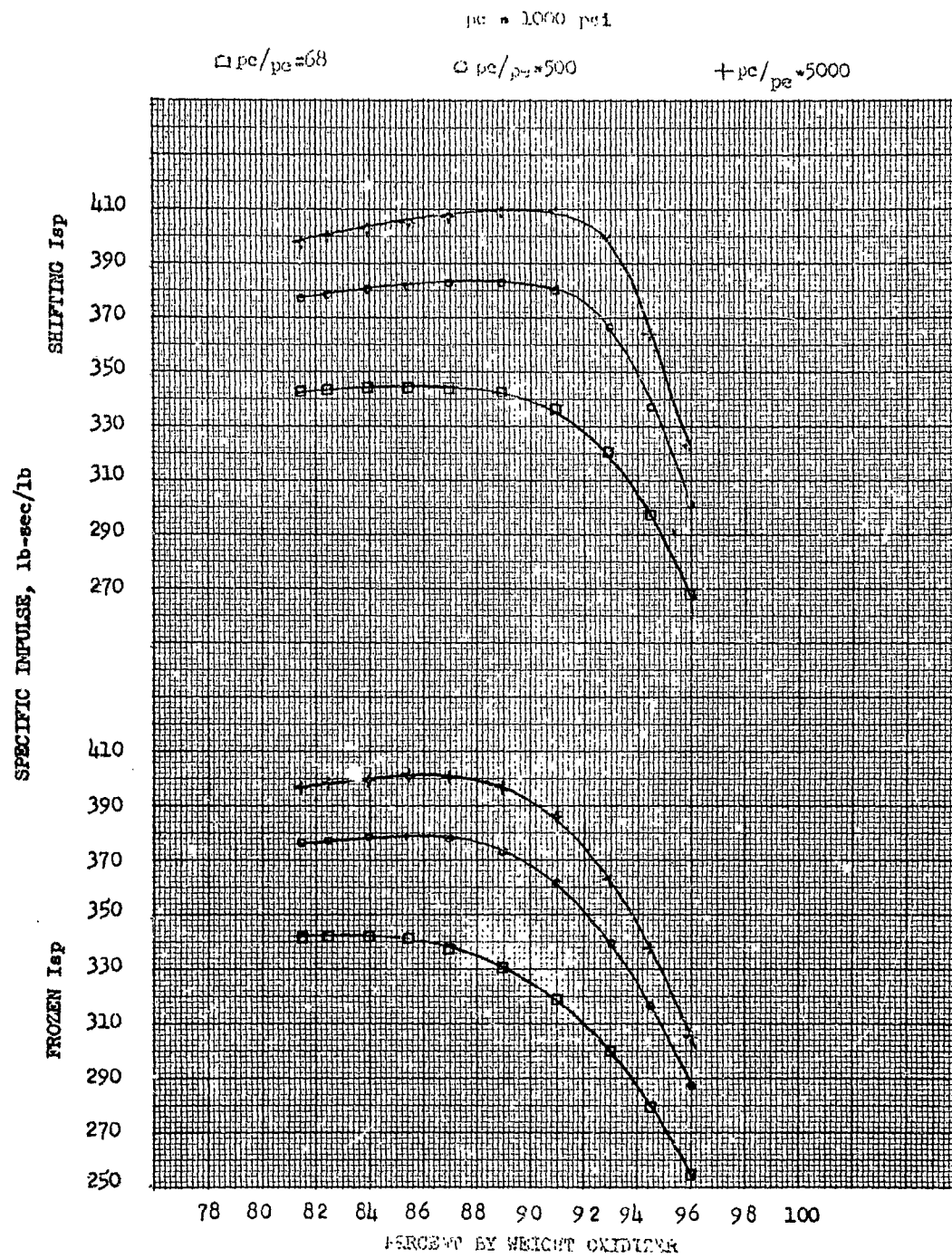
LIQUID HYDROGEN - CHLORINE TRIFLUORIDE 1-1 MIXTURES (FIGURE 20)

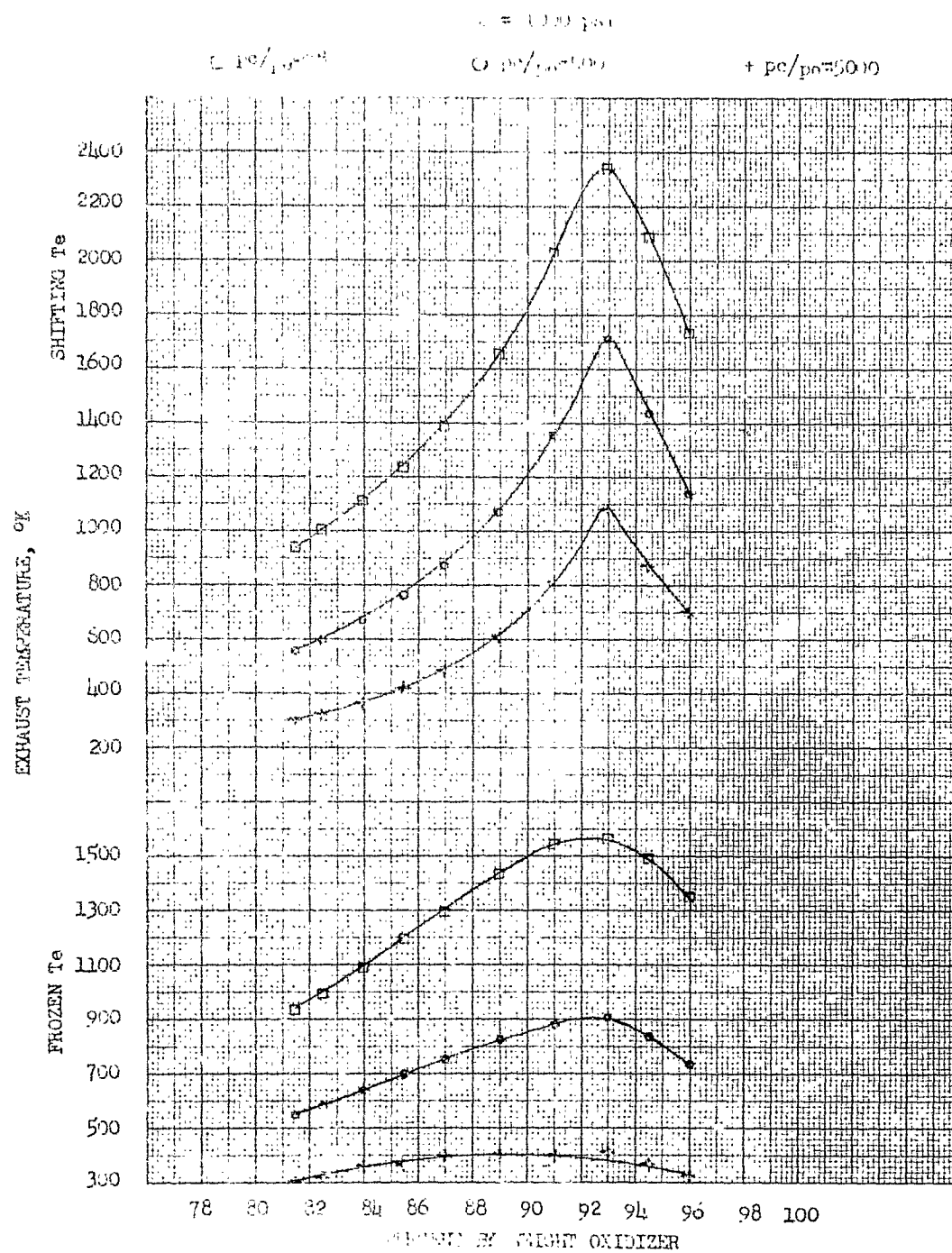


LIQUID HYDROGEN - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 21

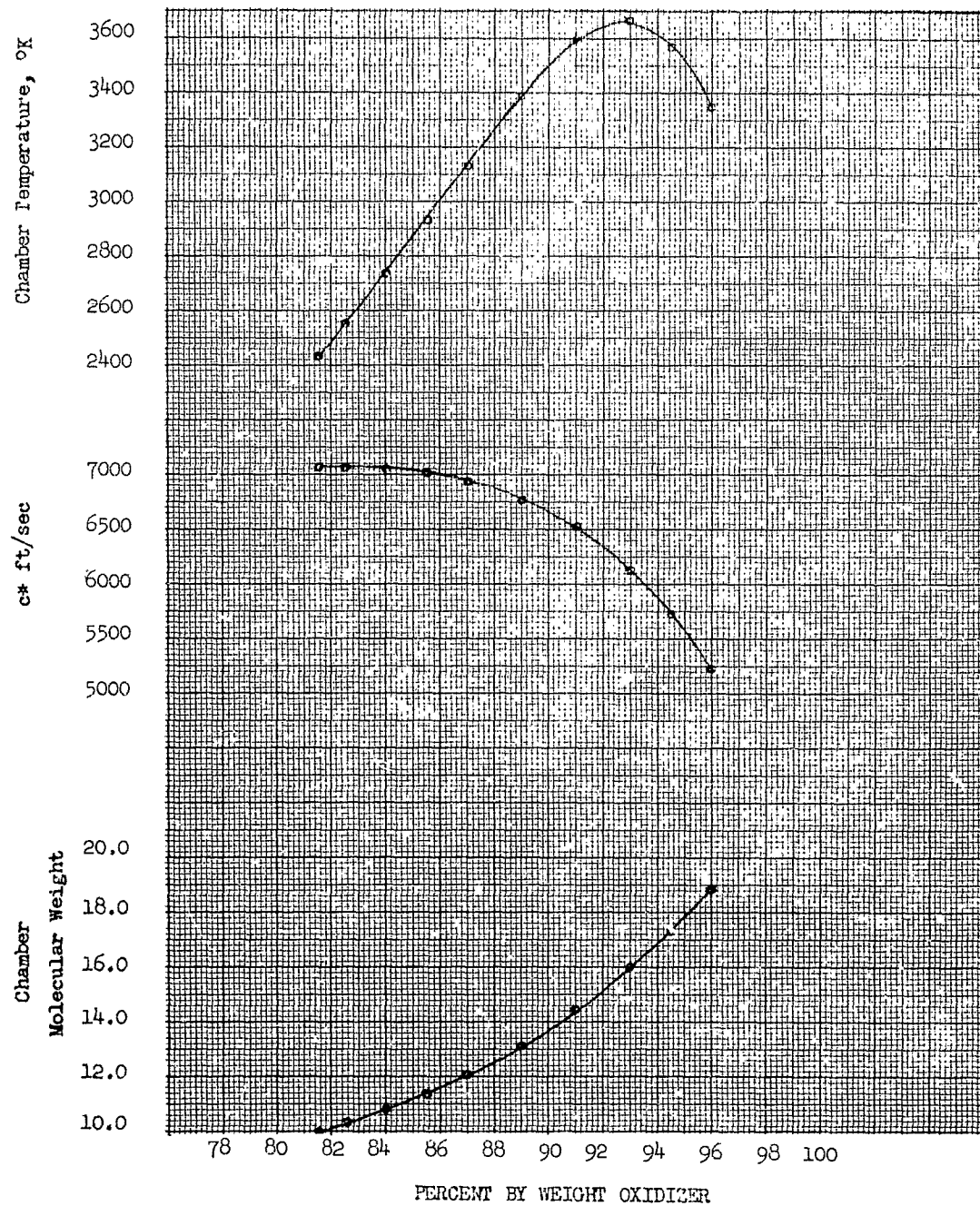


LIQUID HYDROGEN - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 22

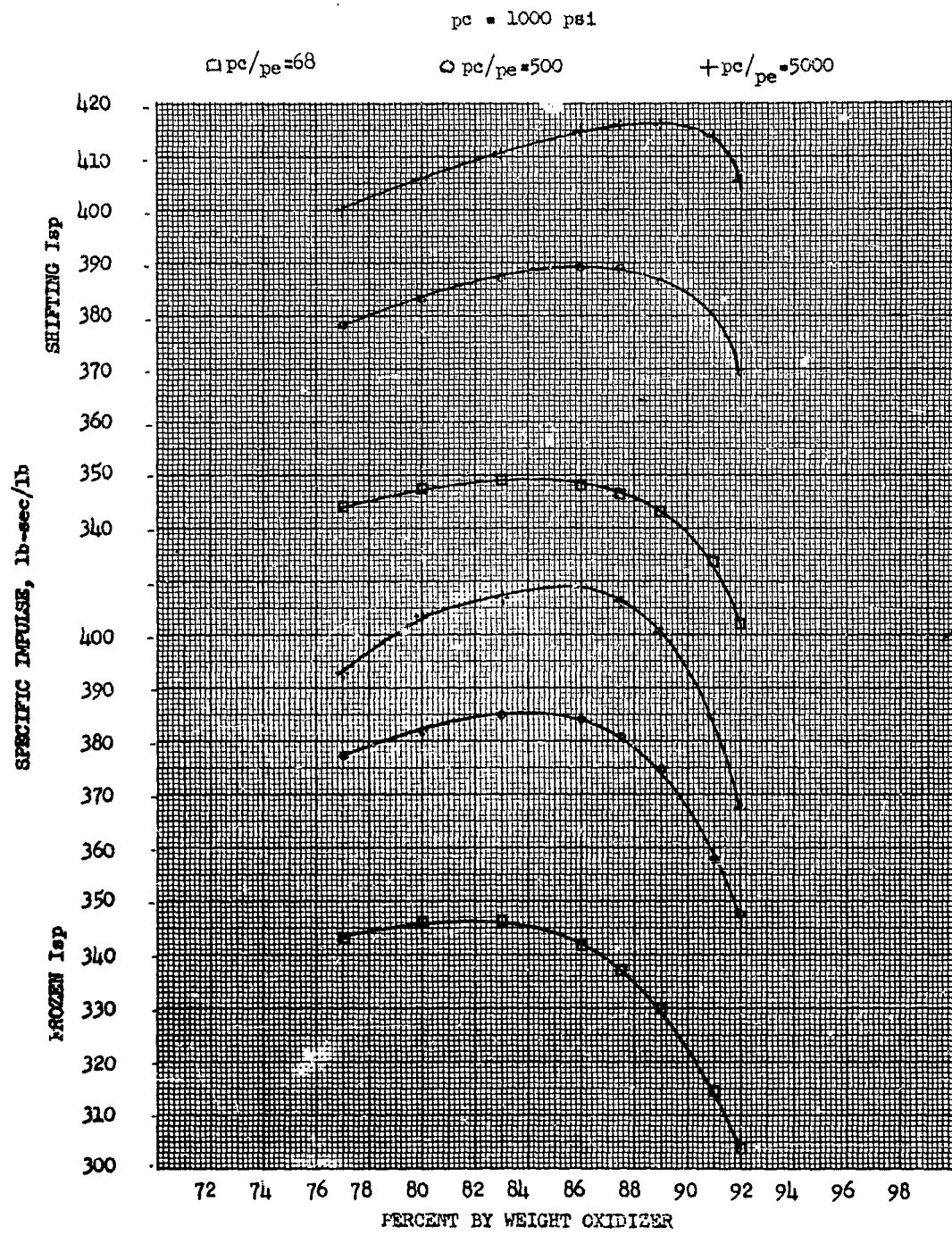




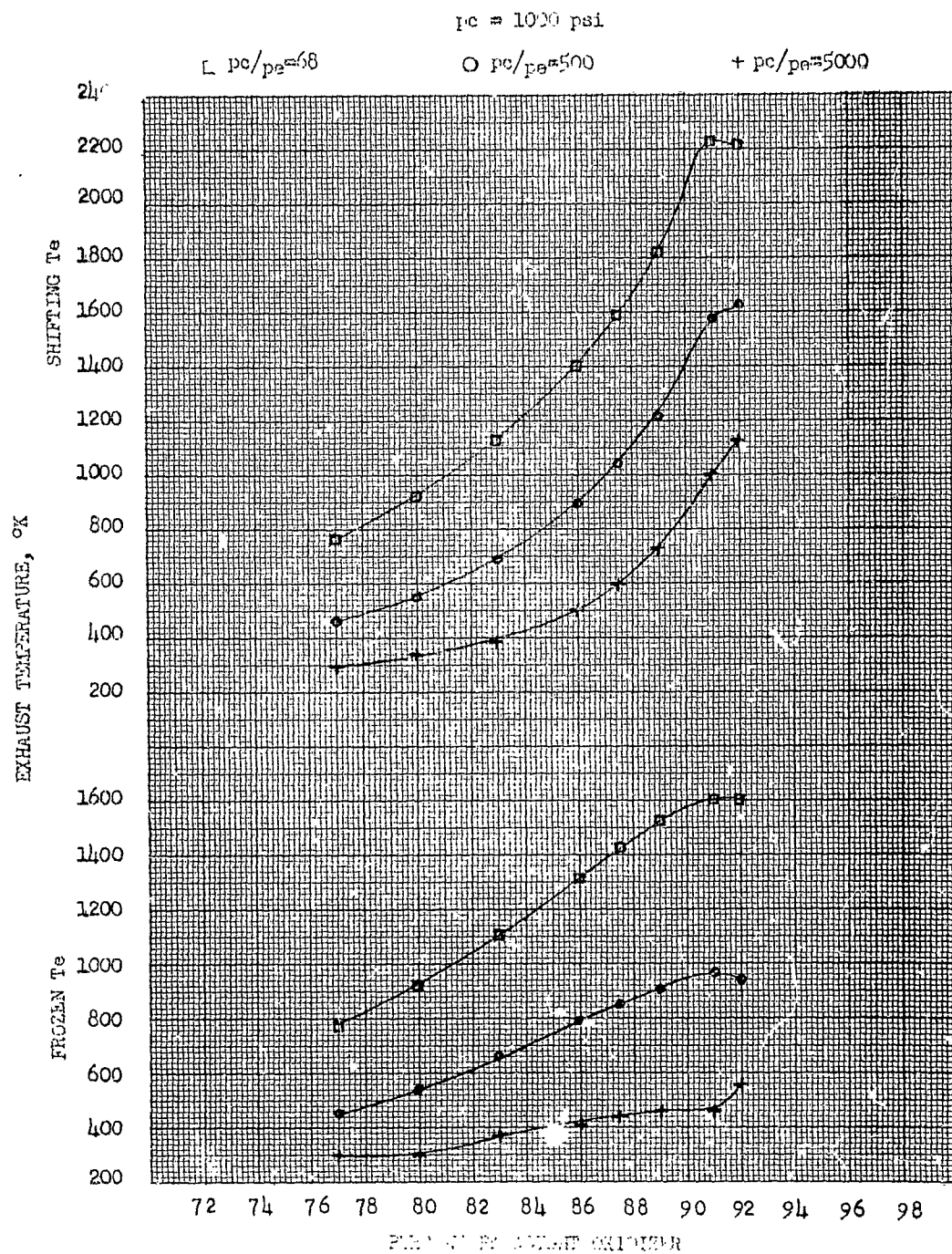
LIQUID HYDROGEN - PERCHLORYL FLUORIDE BURNING RATE - CHAMBER TEMPERATURE



LIQUID HYDROGEN - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 25



LIQUID HYDROGEN - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 26



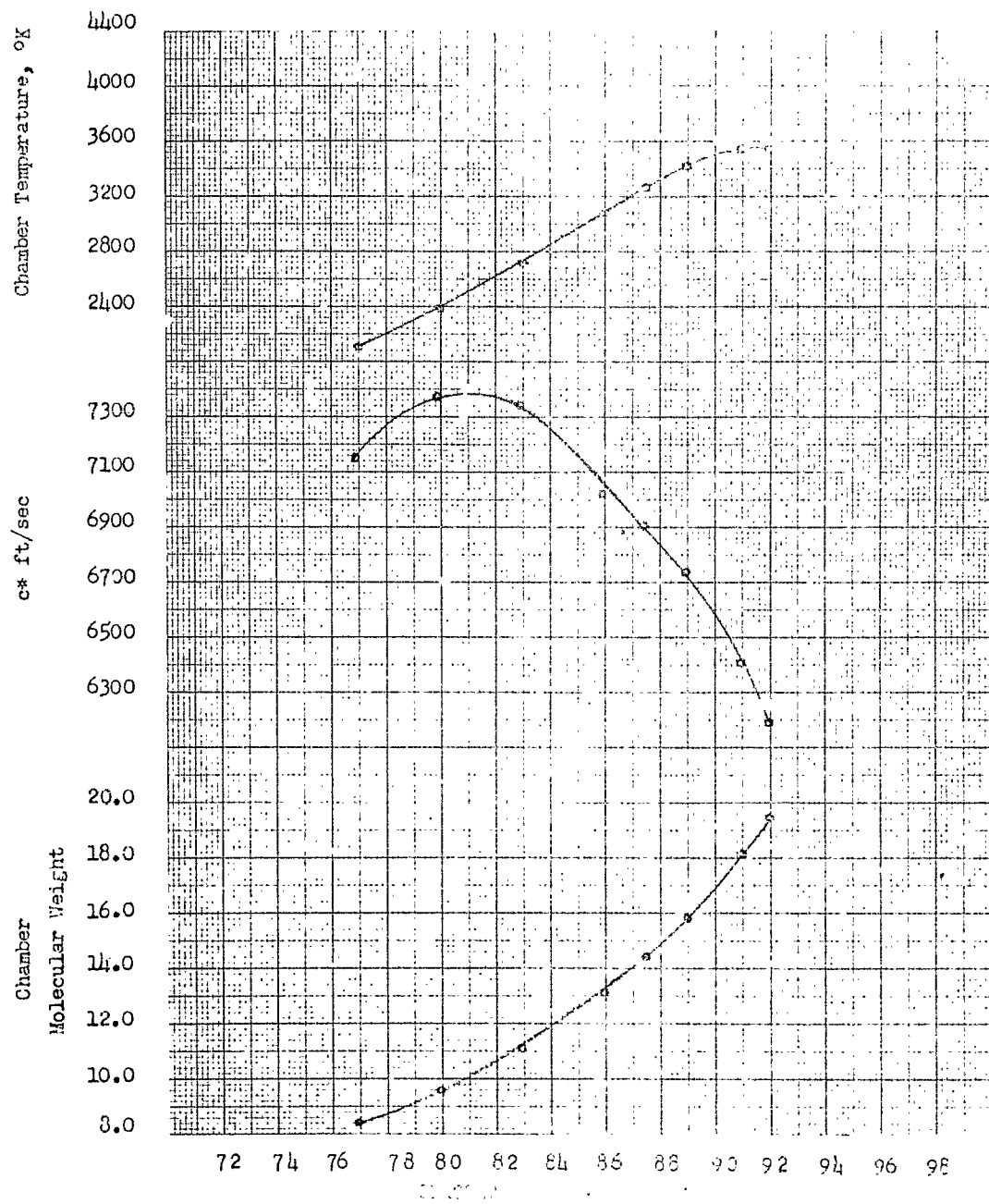
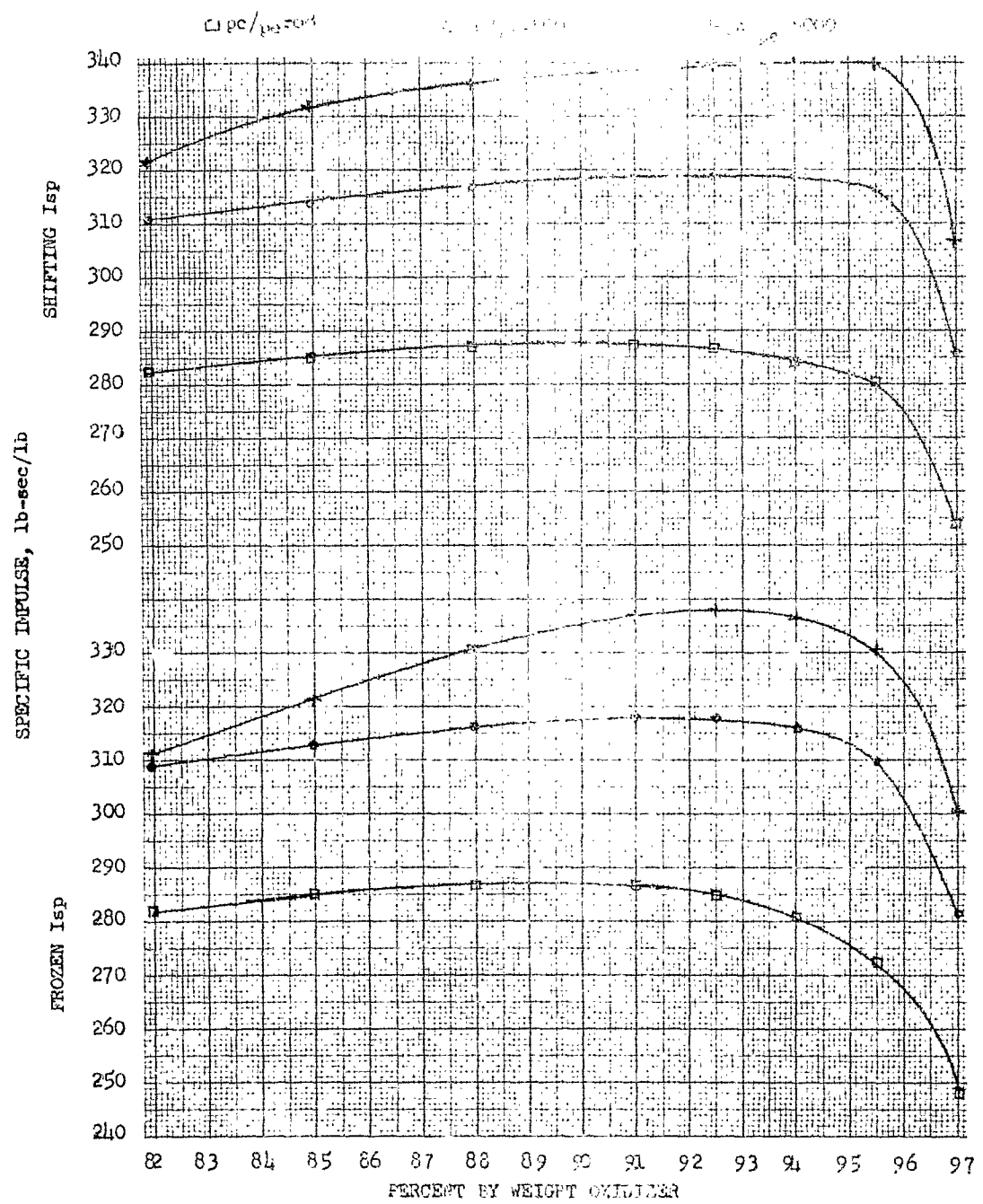
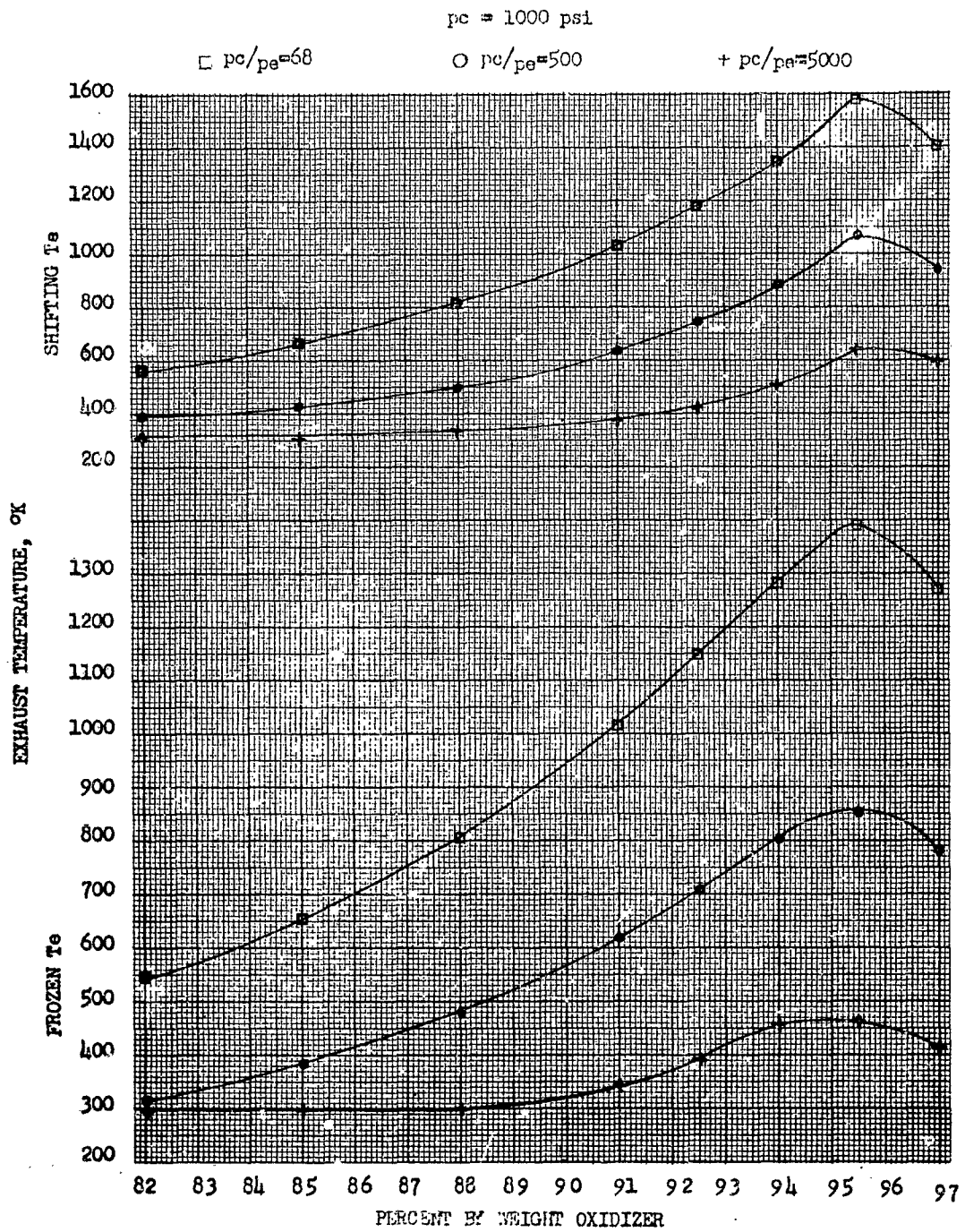


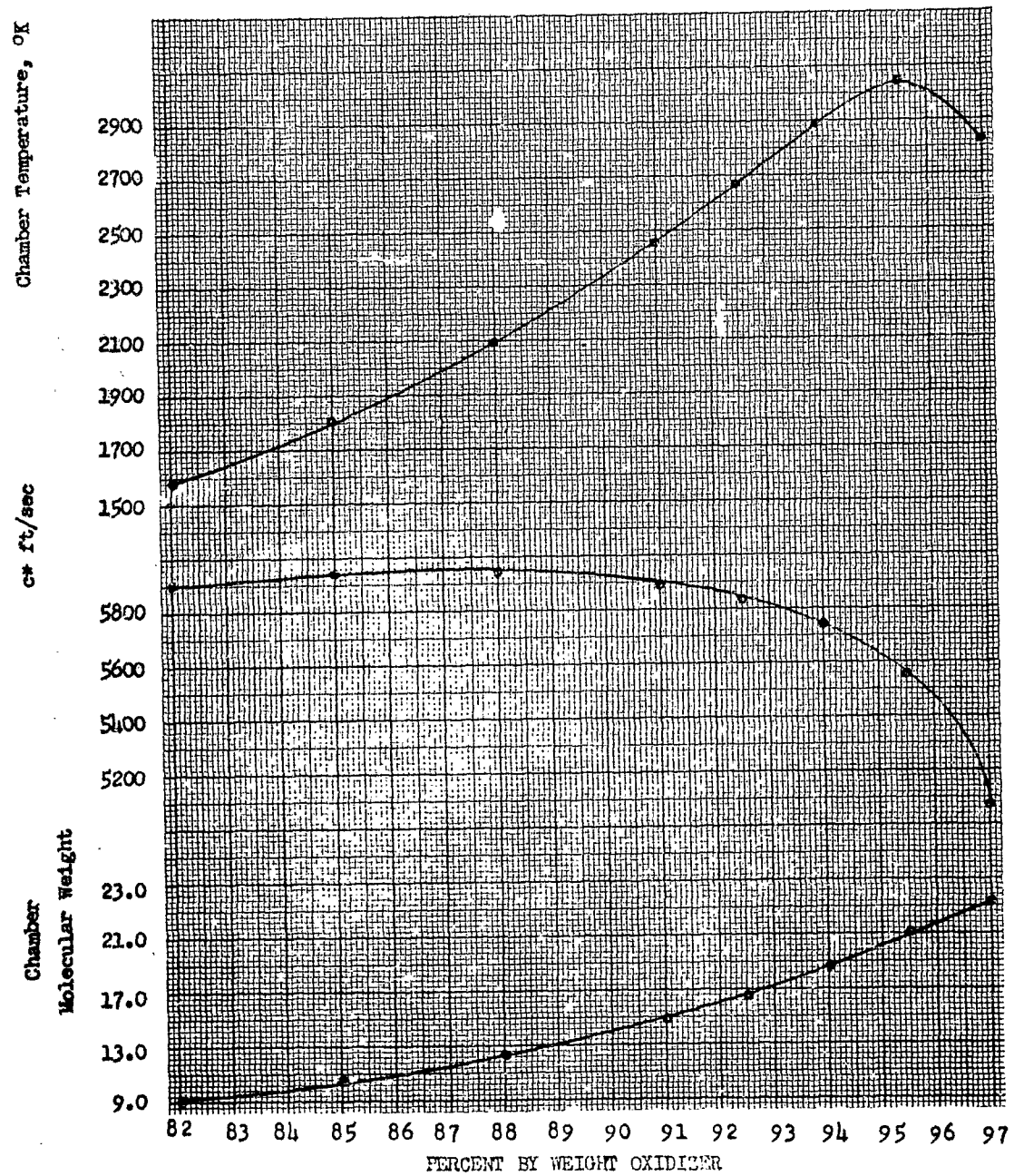
Fig. 1. (continued)



LIQUID HYDROGEN - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 29



LIQUID HYDROGEN - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 30



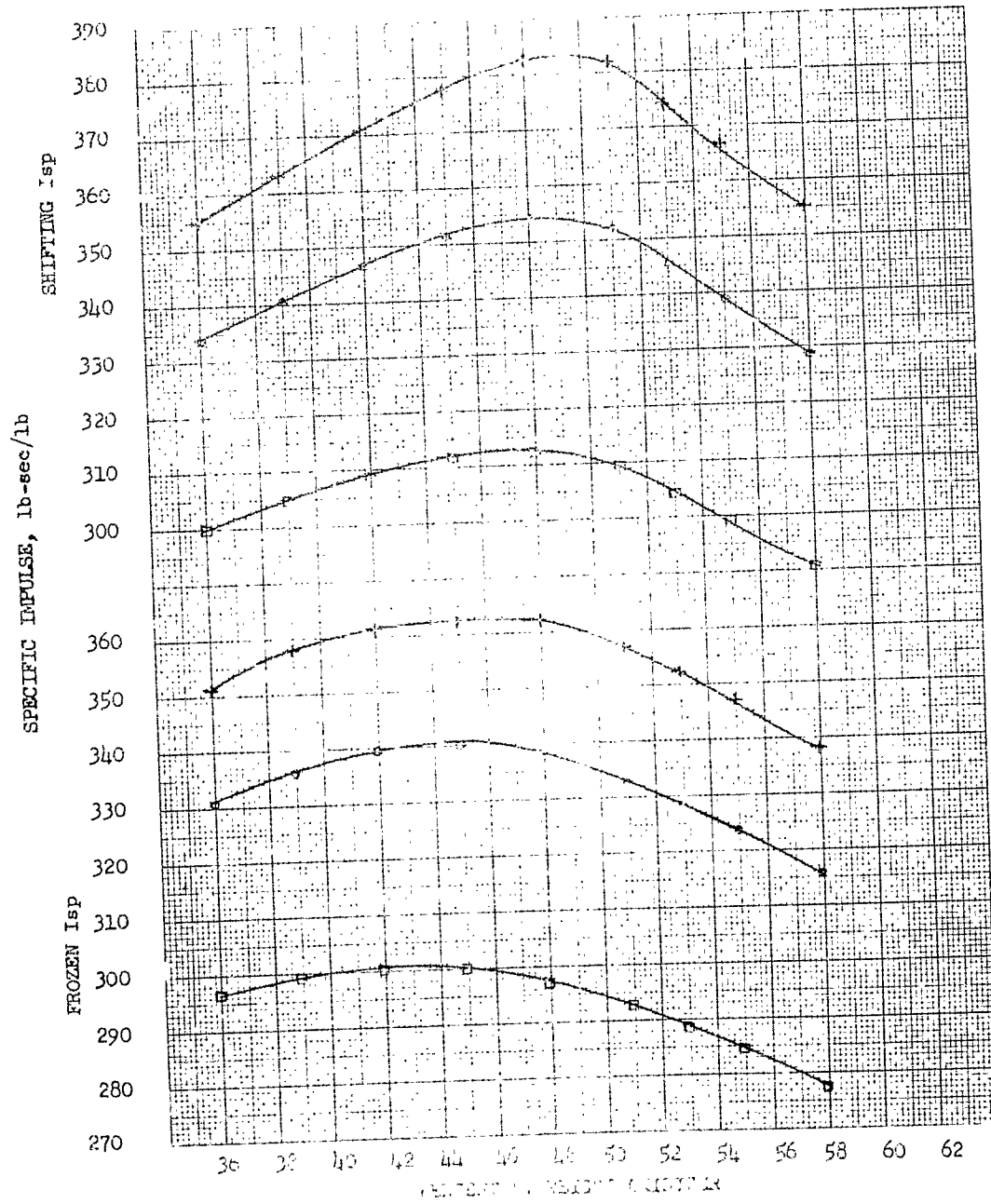
HYDRAULIC ...

...

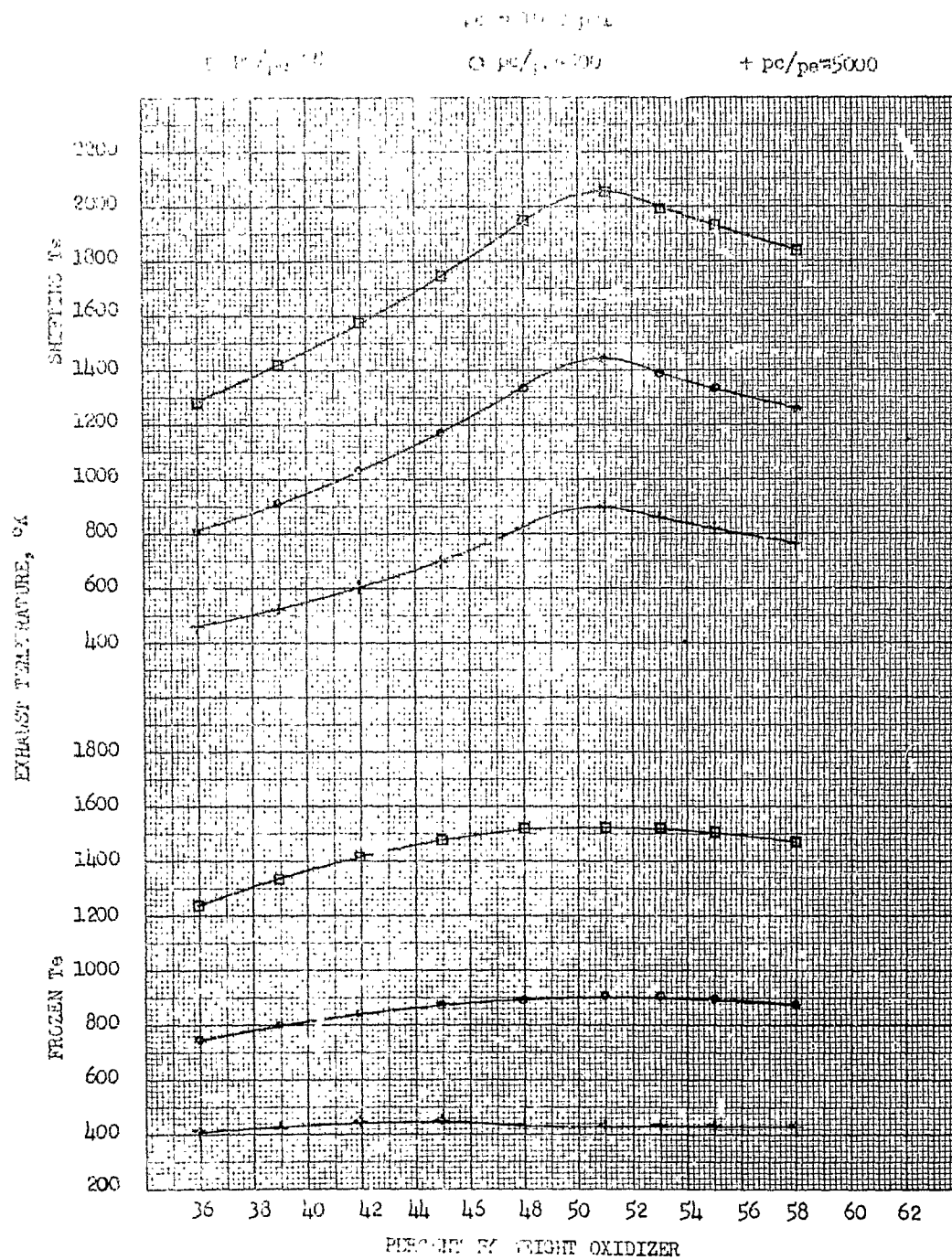
...

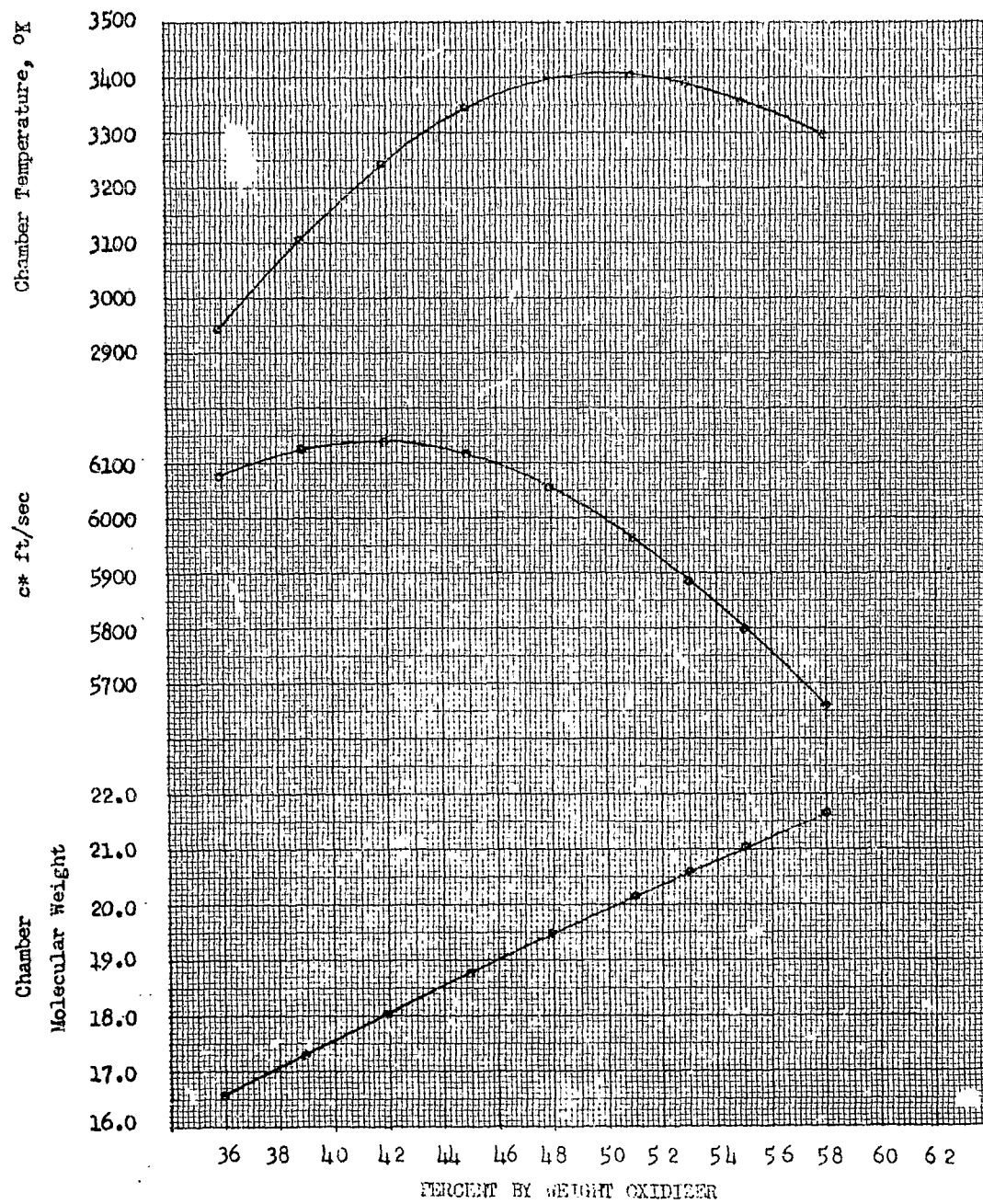
...

$+ve/10^{5000}$

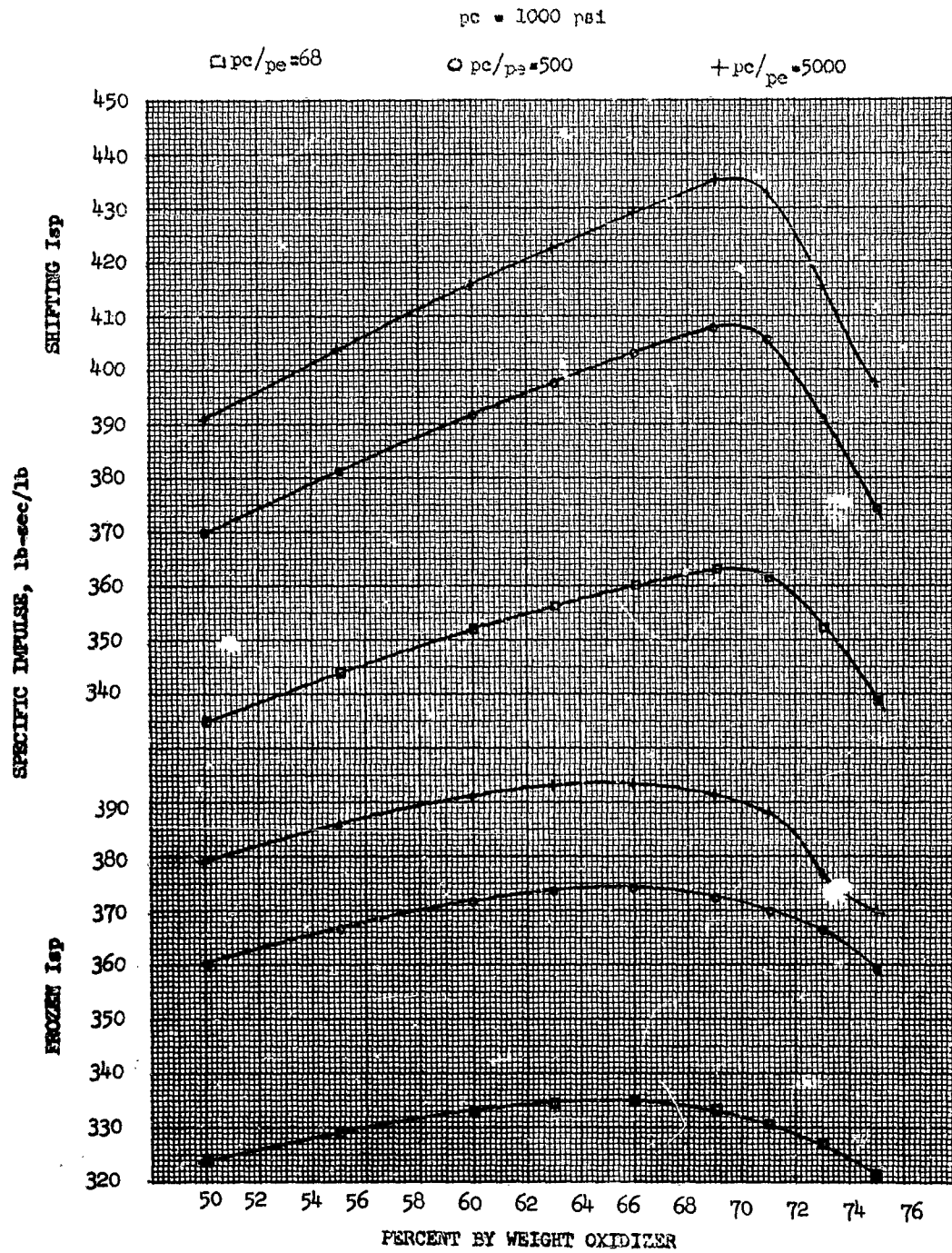


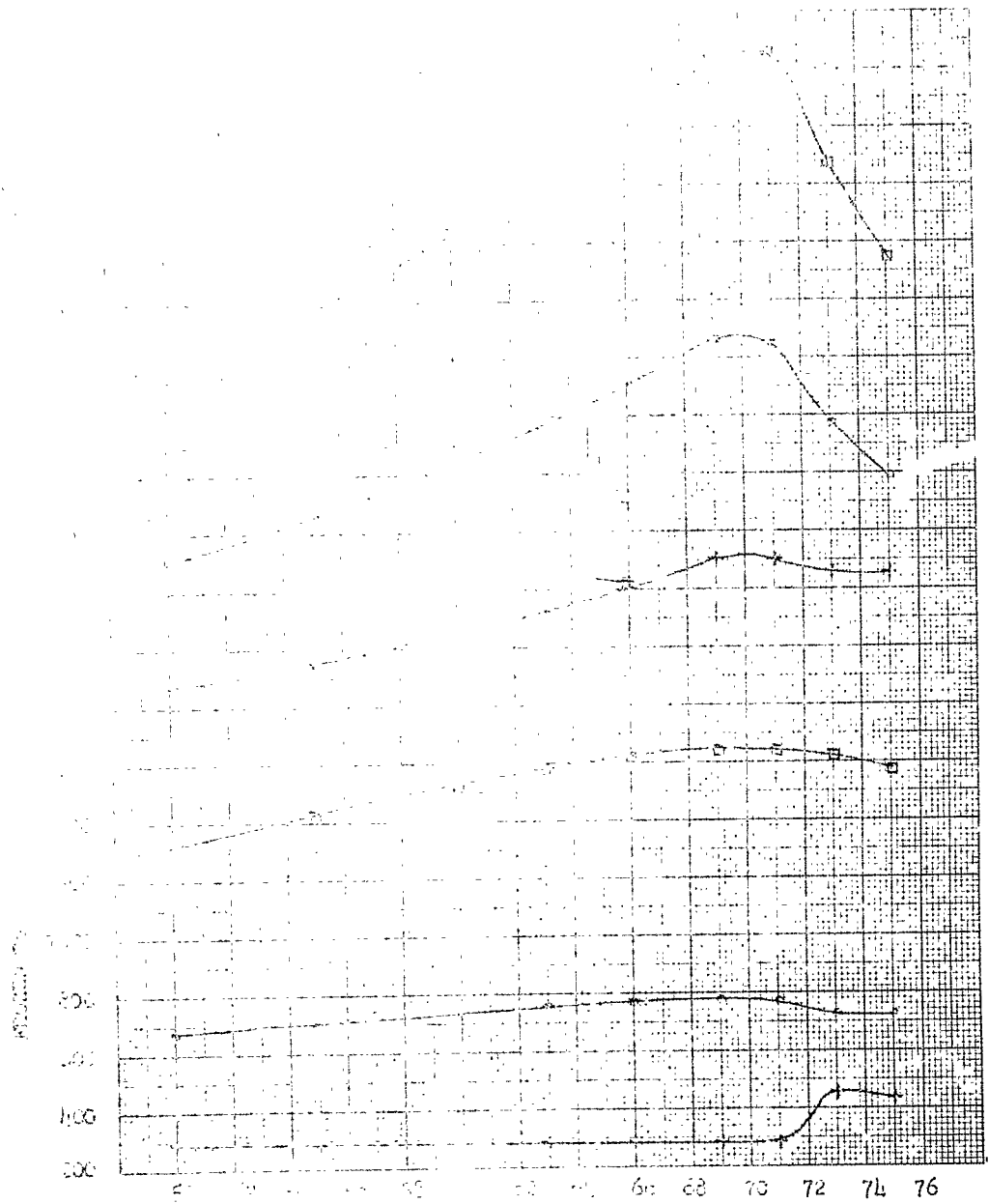
NO. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100





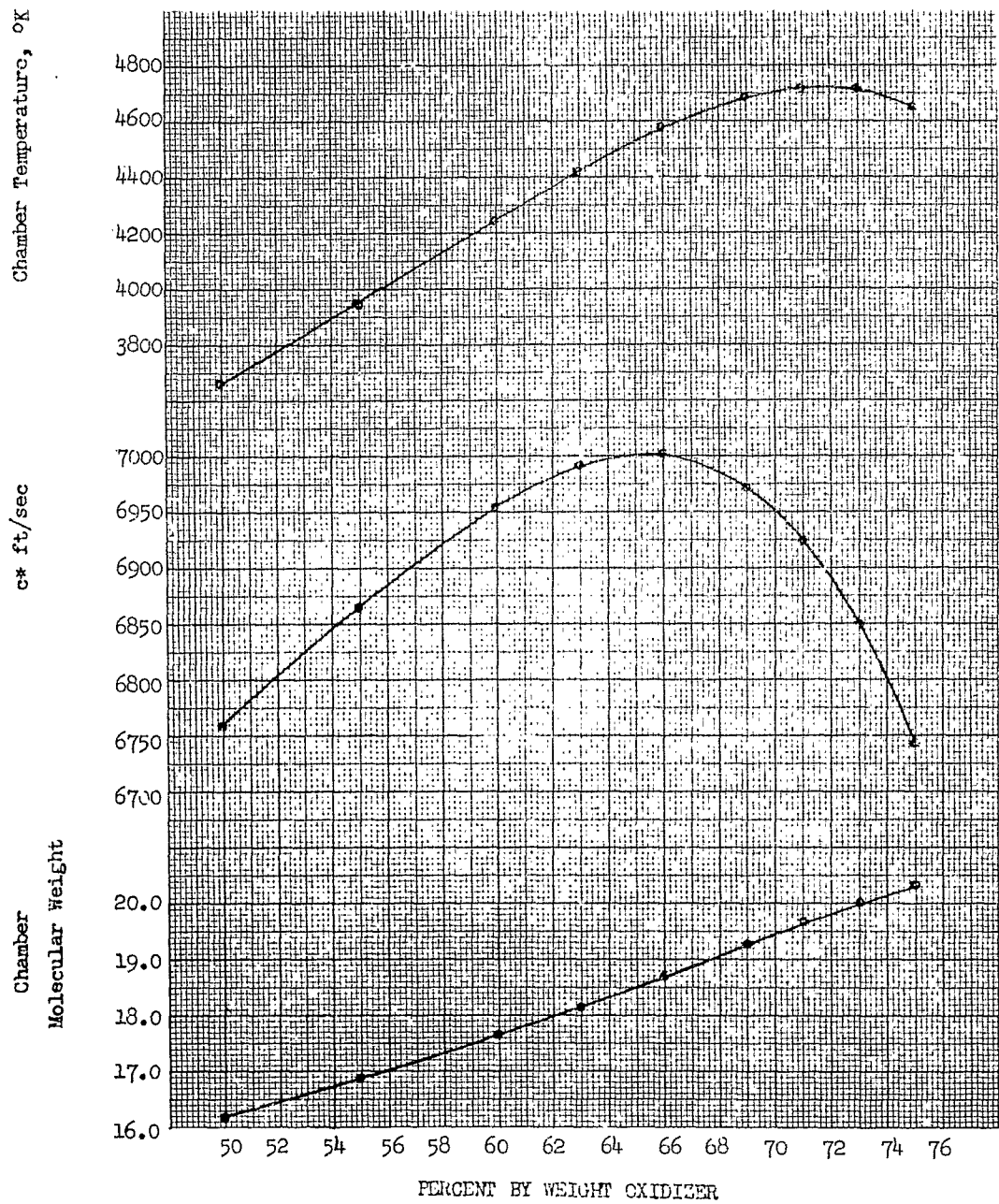
HYDRAZINE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 34



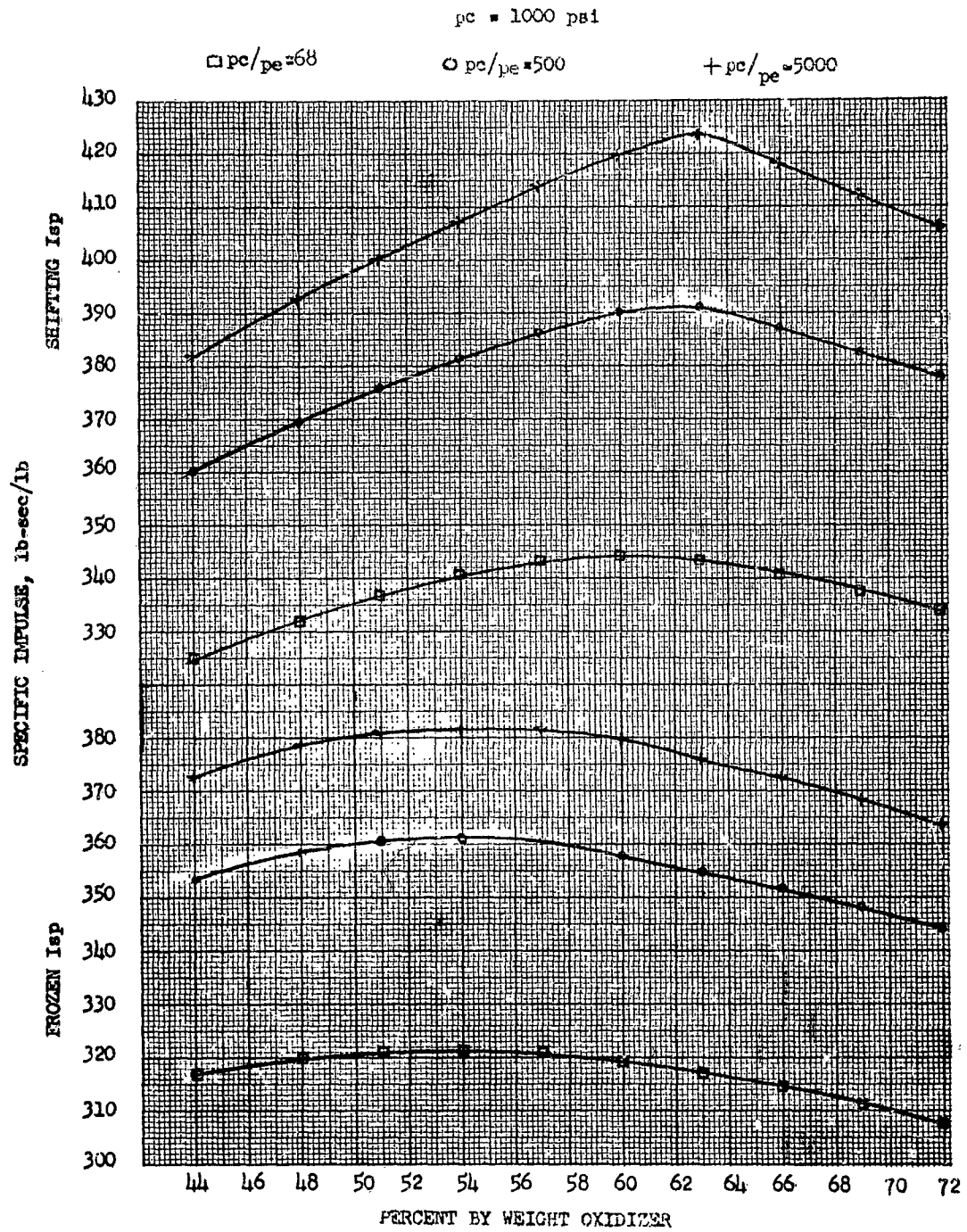


Source: U.S. Census Bureau

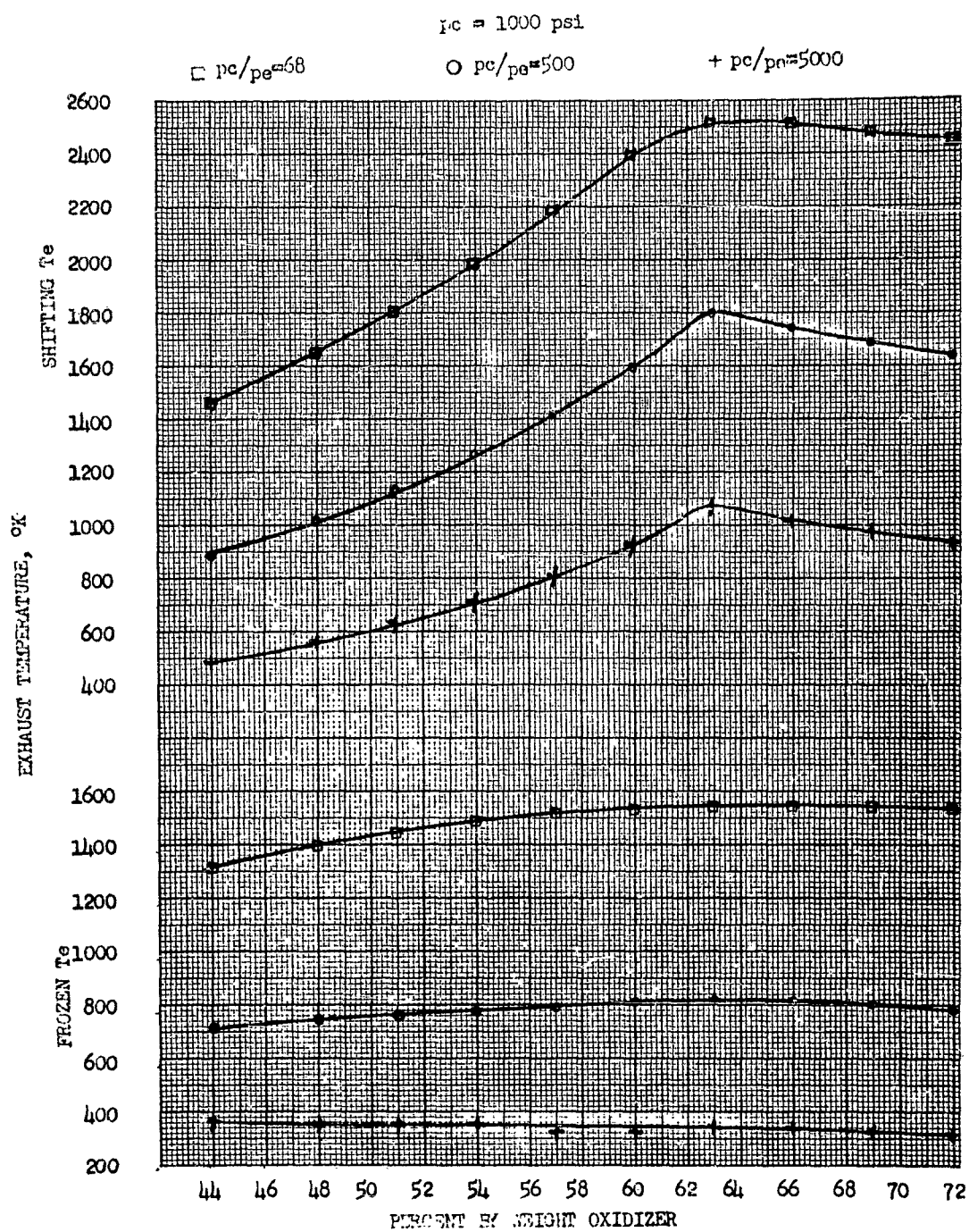
HYDRAZINE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 10

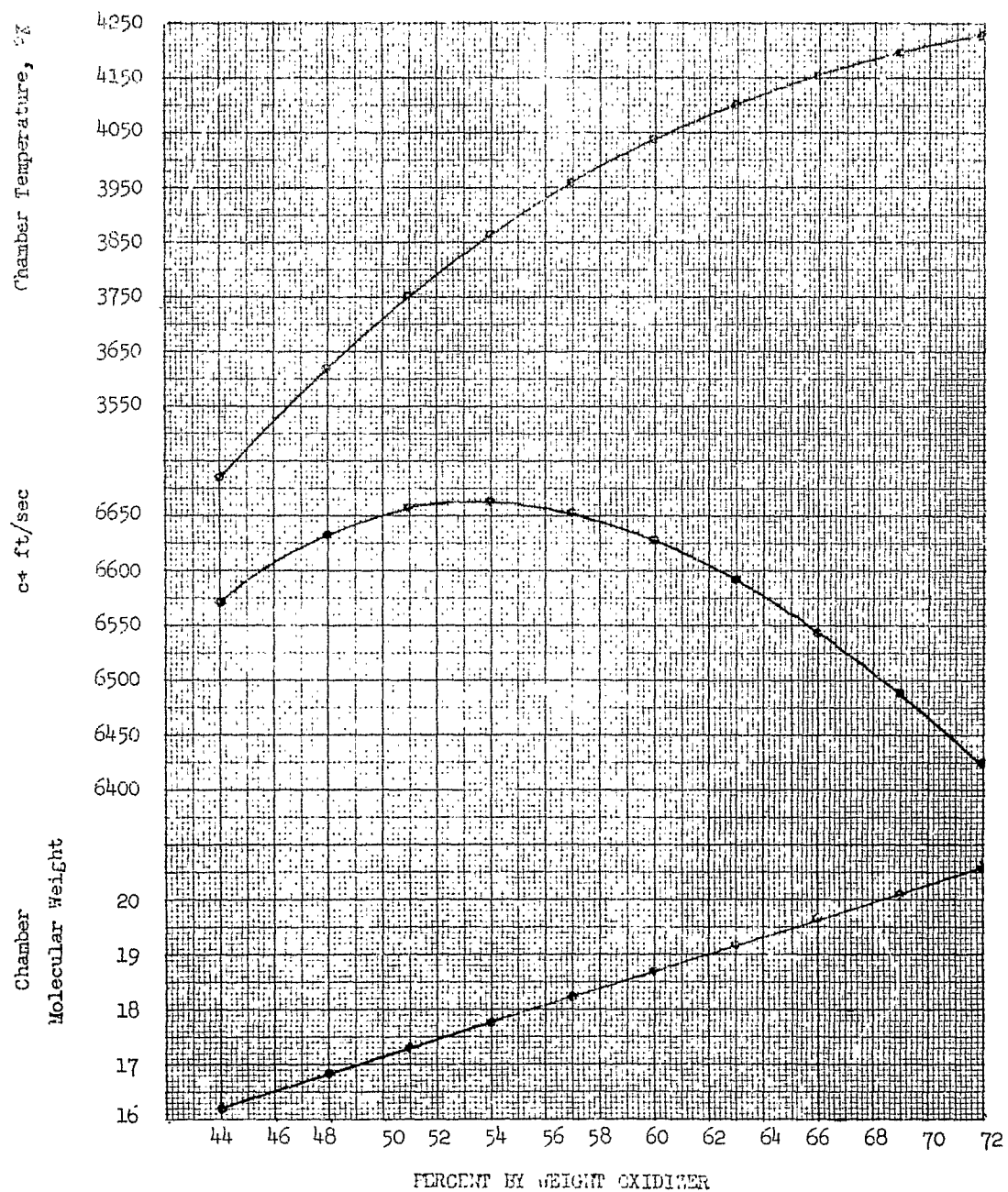


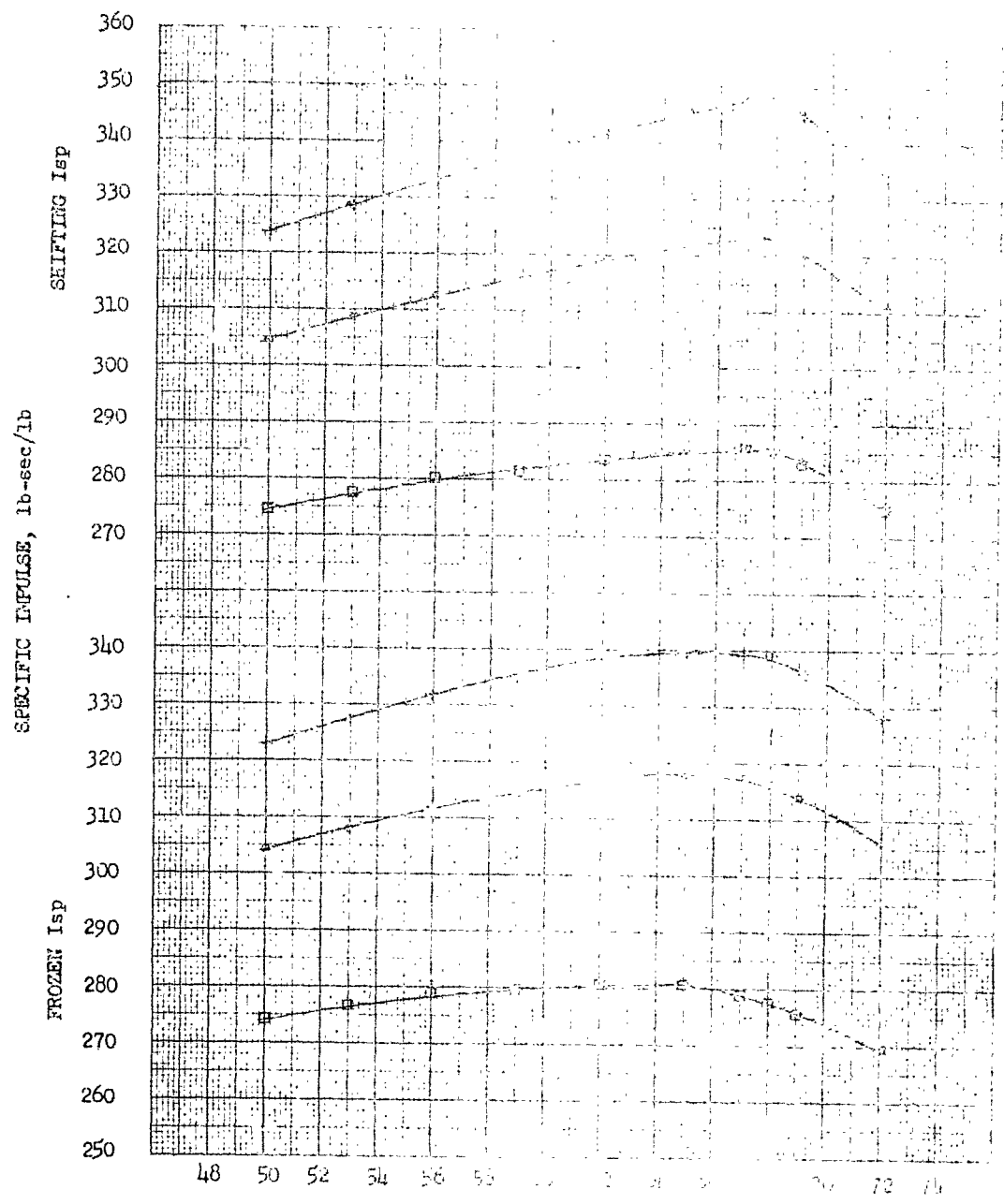
HYDRAZINE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 37



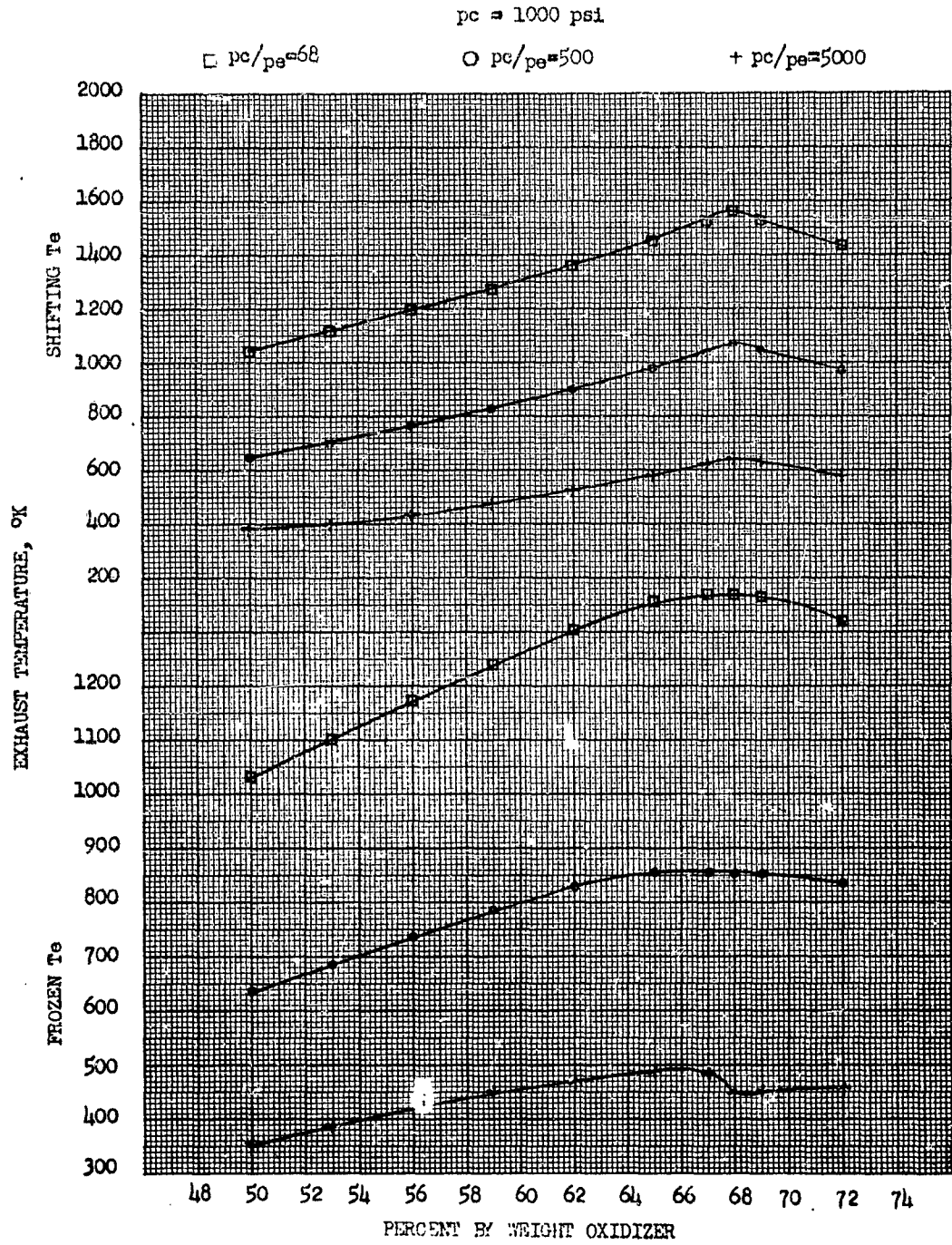
HYDRAZINE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 38



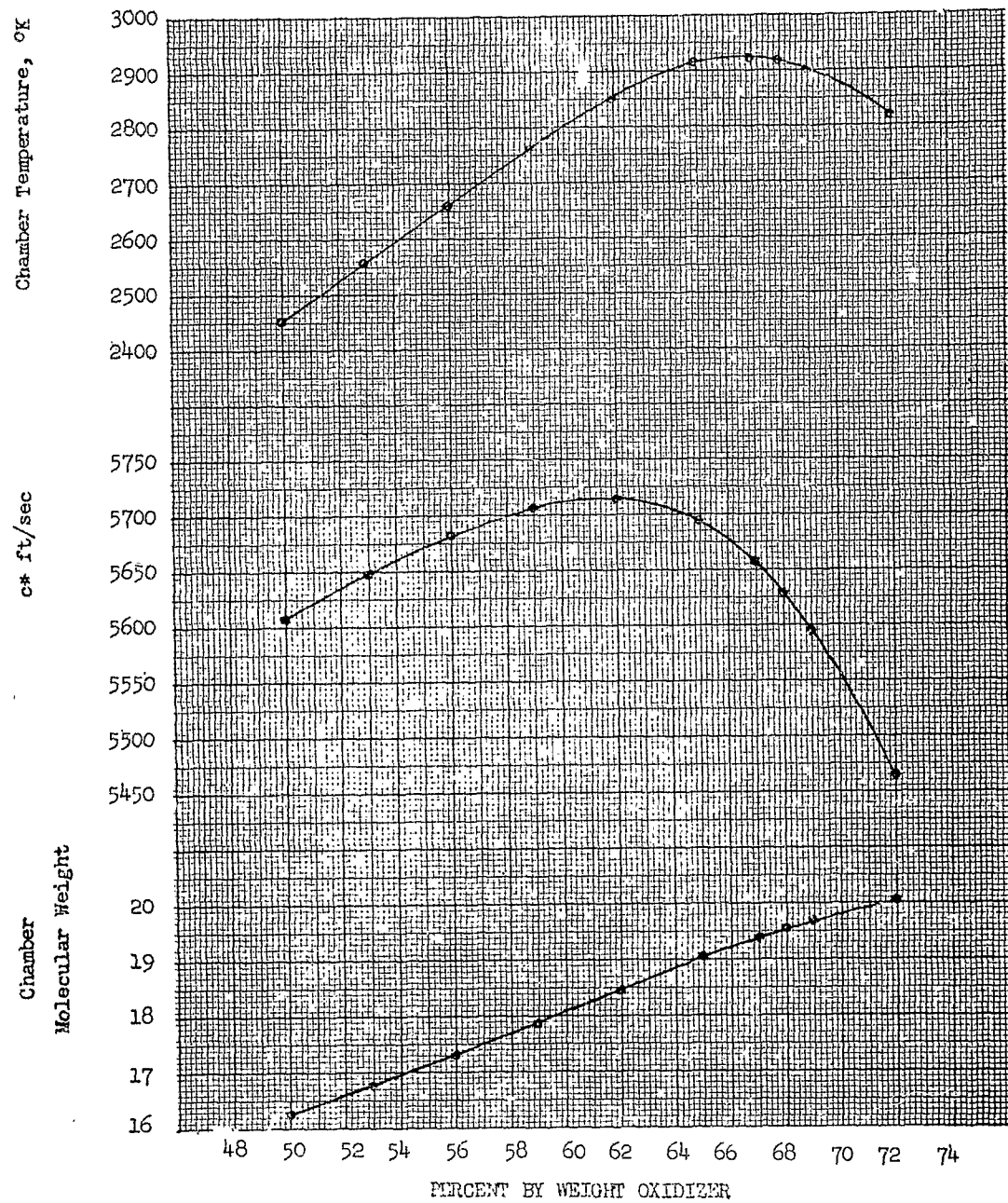




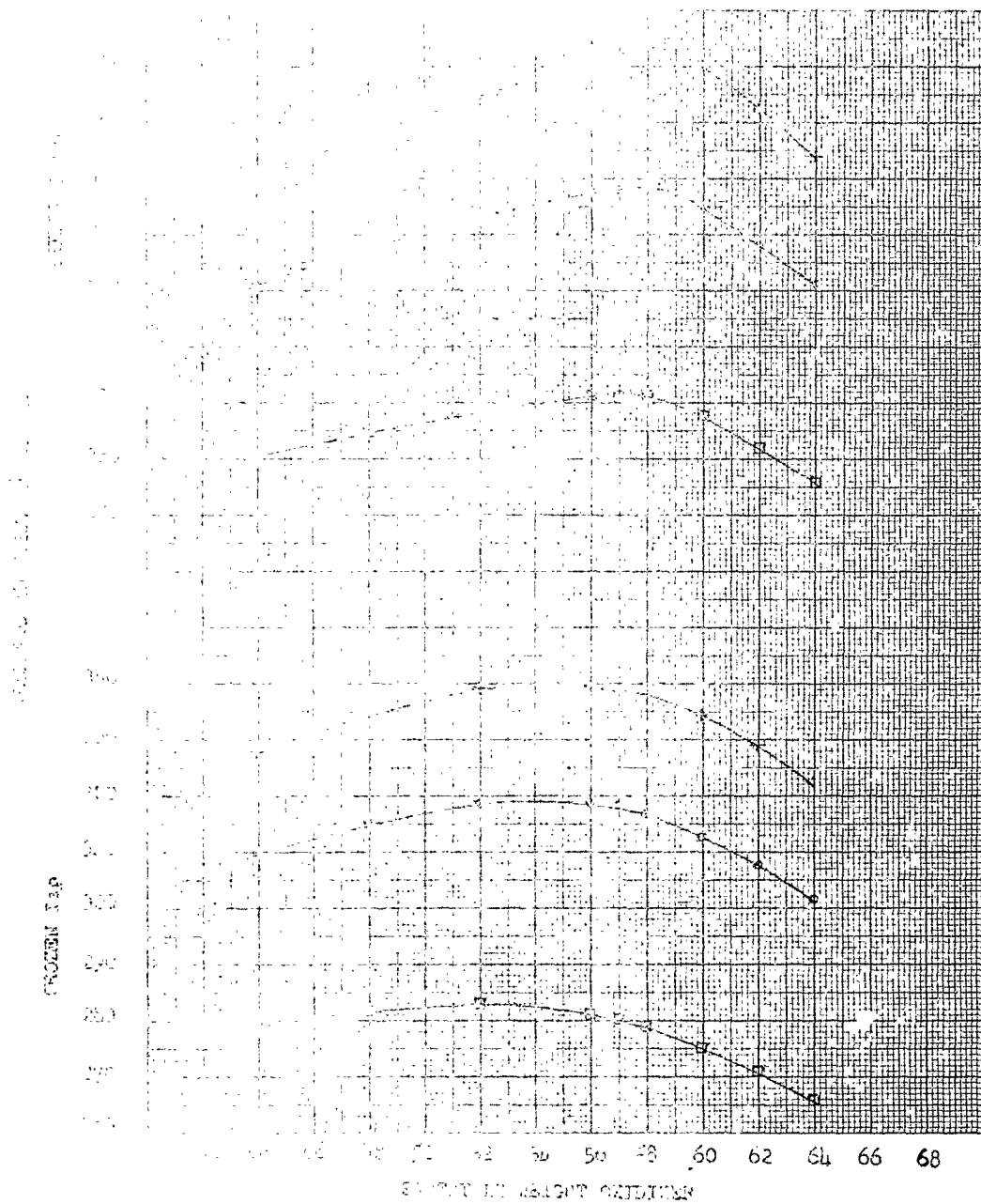
HYDRAZINE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 41



HYDRAZINE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 42



1000/1000 = 1000



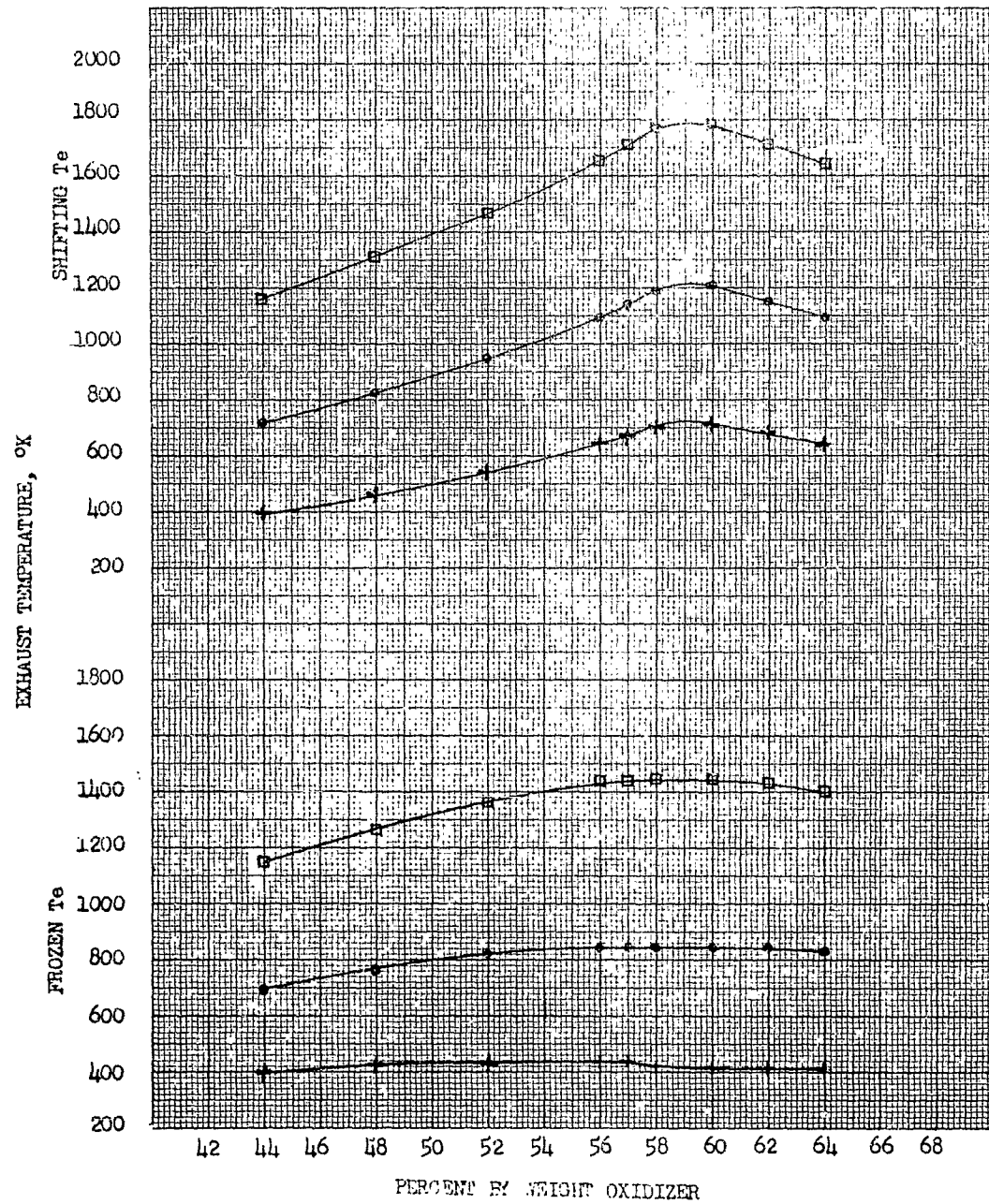
HYDRAZINE - HYDROGEN PEROXIDE PROPELLANT COMPOSITIONS

$p_c = 100 \text{ psi}$

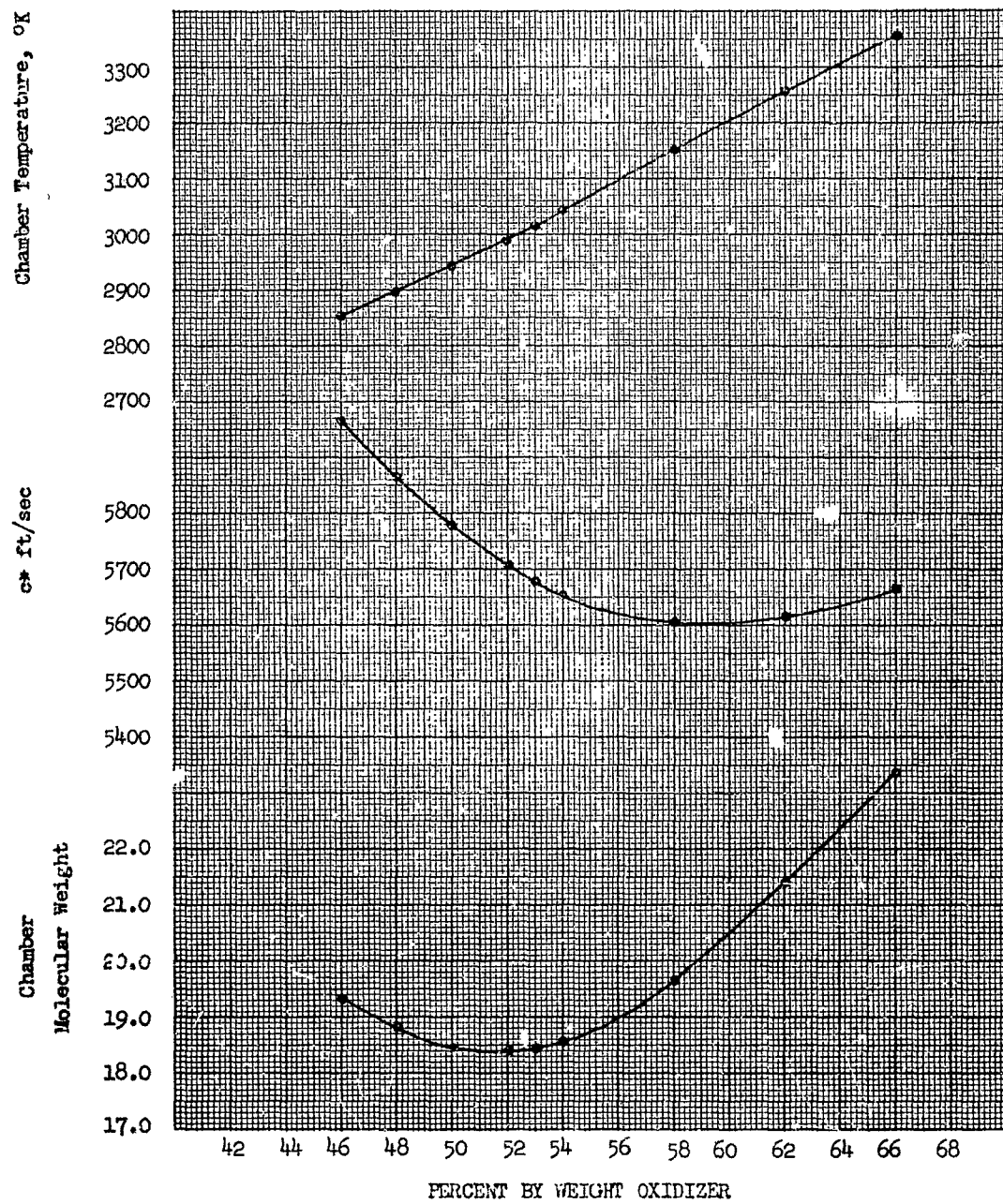
$L \text{ } p_c/p_a = 58$

$O \text{ } p_c/p_a = 100$

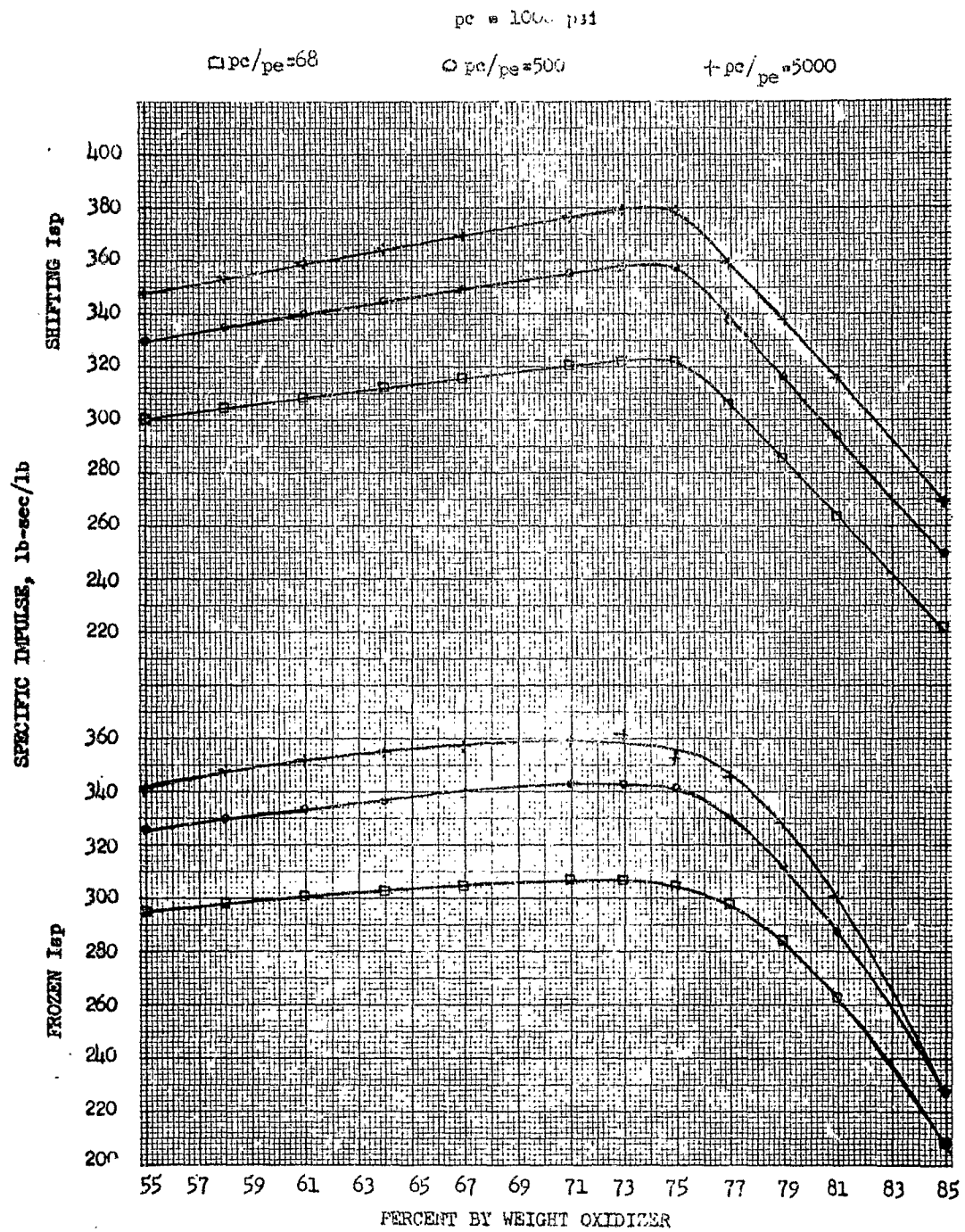
$I \text{ } p_c/p_a = 5000$



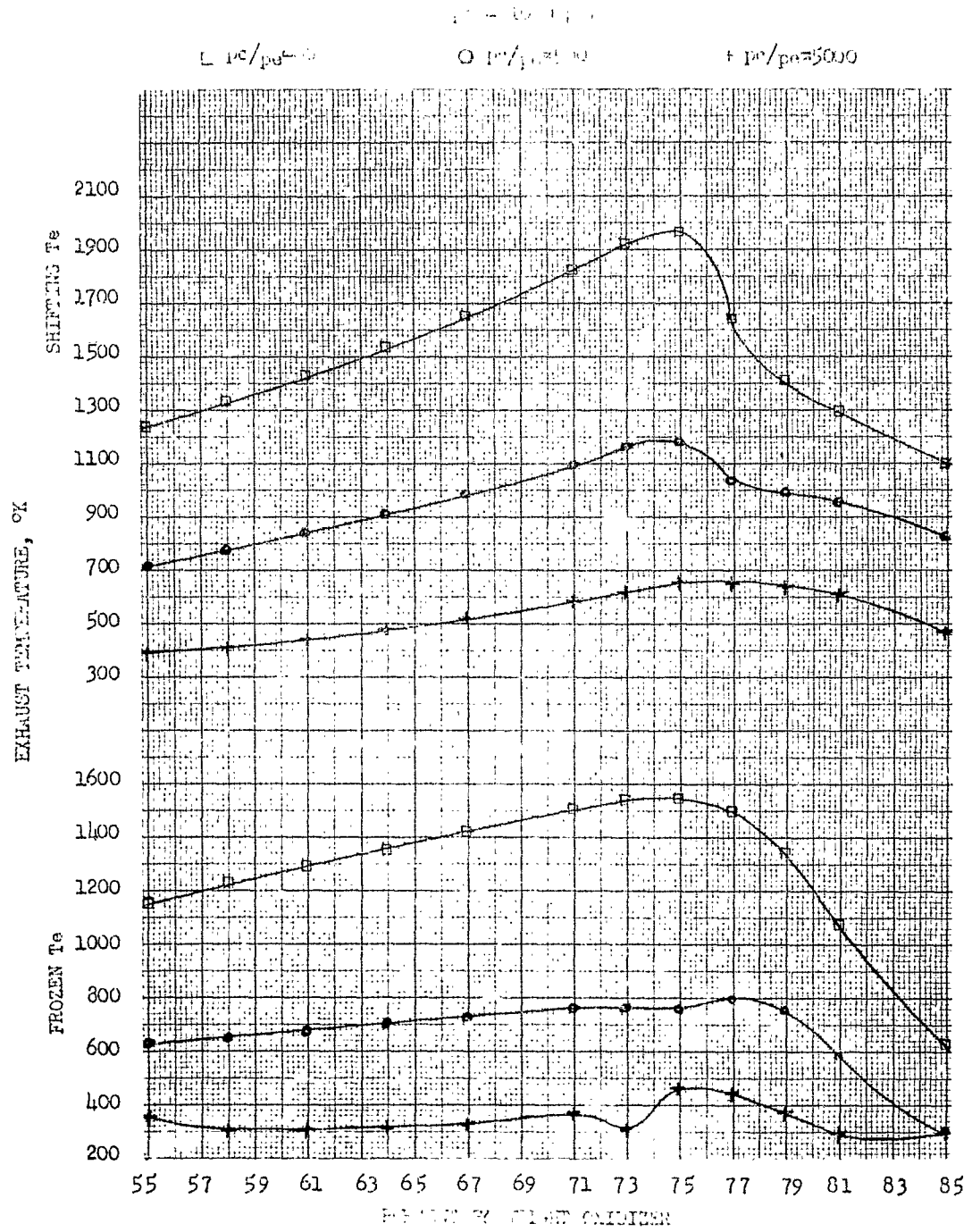
HYDRAZINE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 45



HYDRAZINE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 46



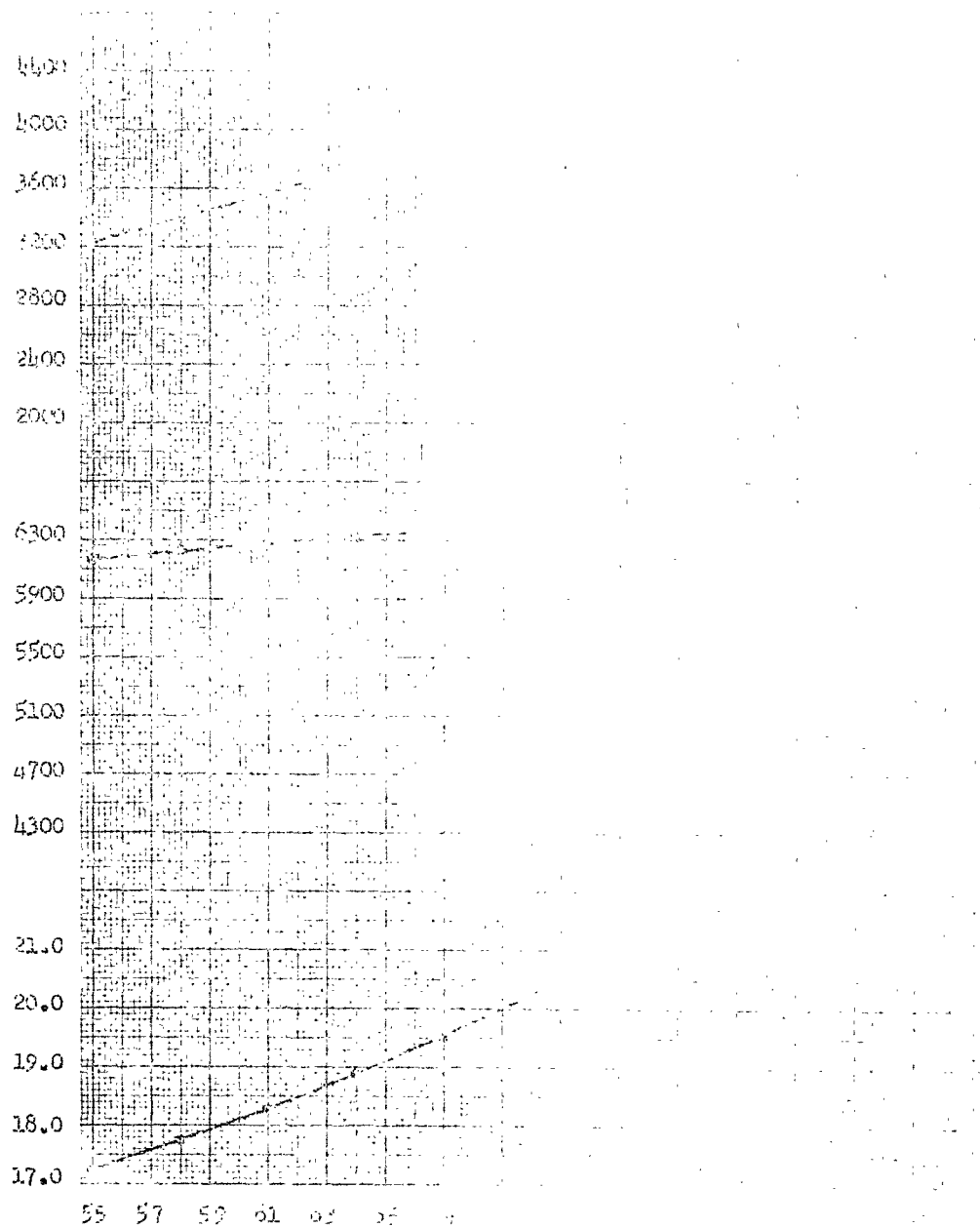
HYDRAZINE - NITROGEN CATALYST PERFORMANCE CURVES FIGURE 47



Chamber Temperature, °F

cm³/sec

Chamber
Molecular Weight

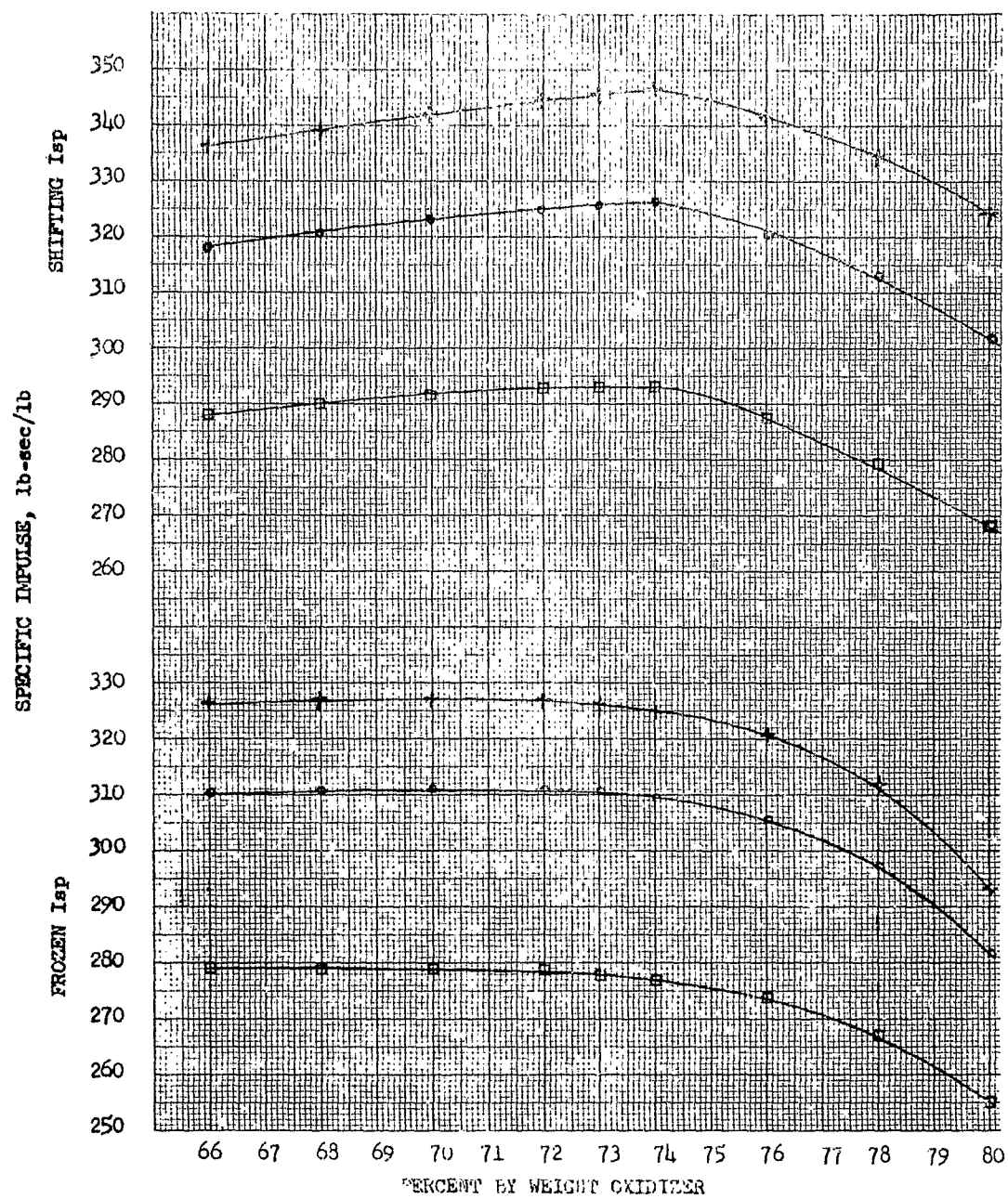


$$f(x) = \frac{1}{2} \ln(x) + \frac{1}{2} \ln(1-x)$$

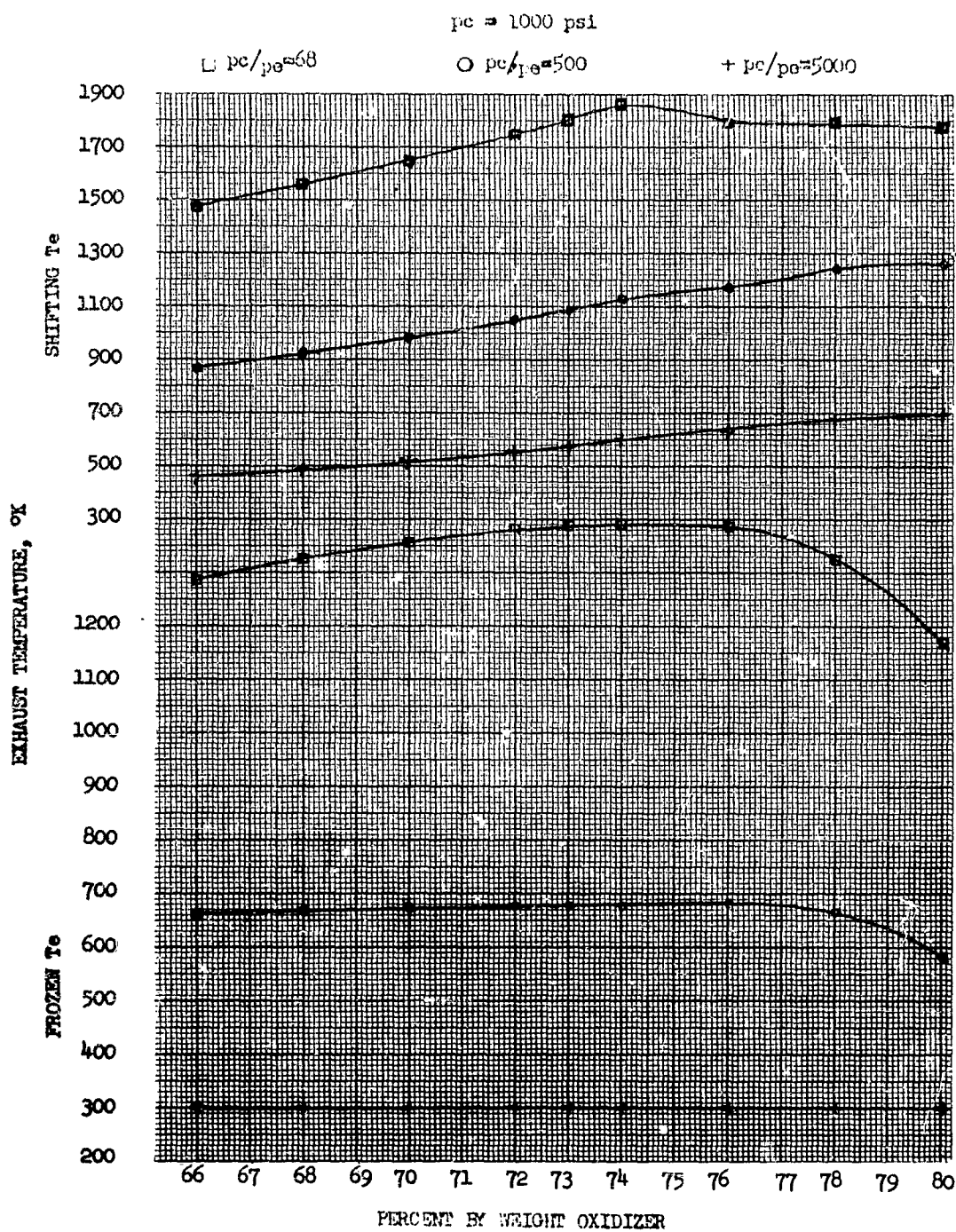
$f_3(r/n, \omega)$

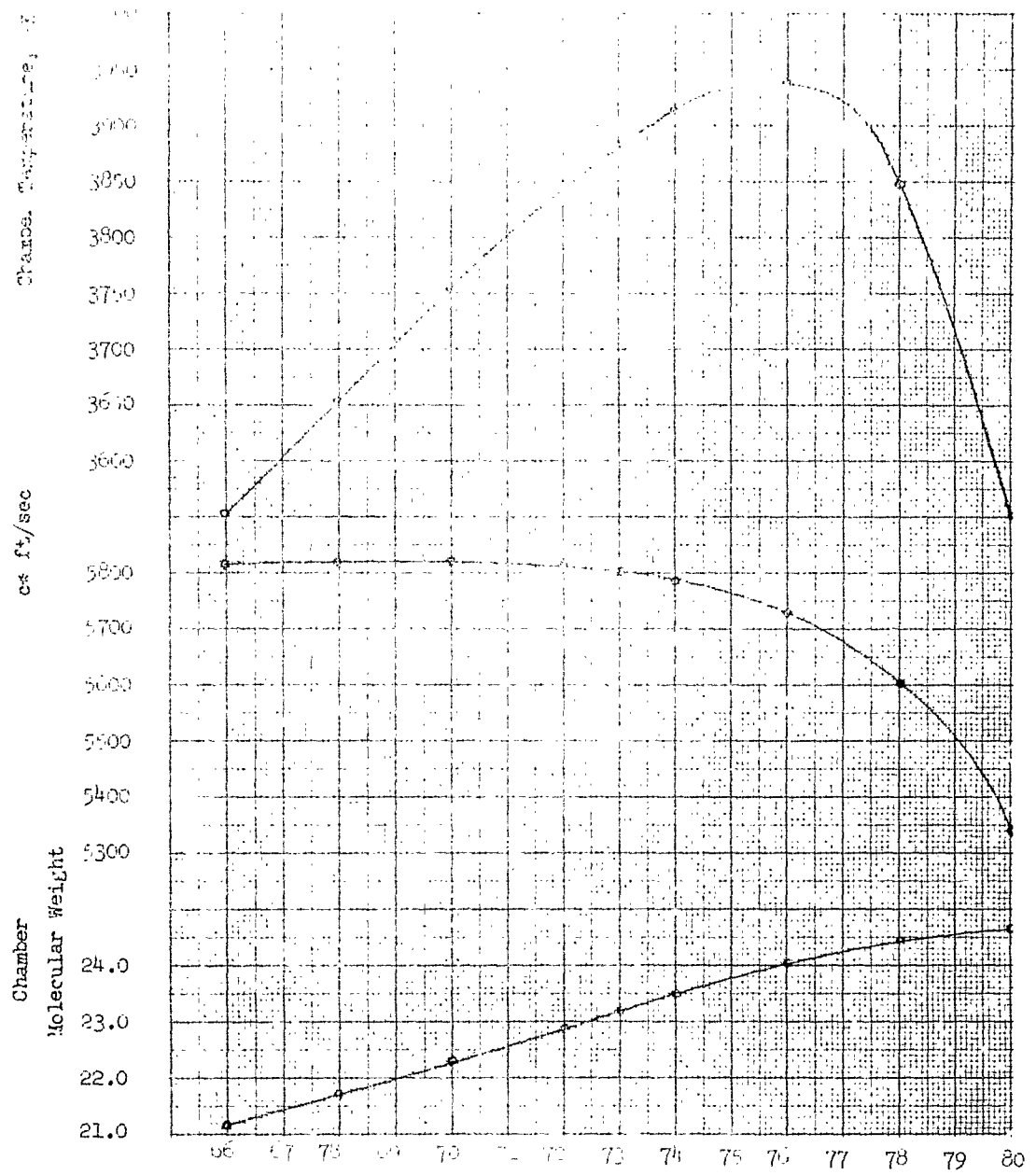
1050 / 1051

+ 10 / p. 5000

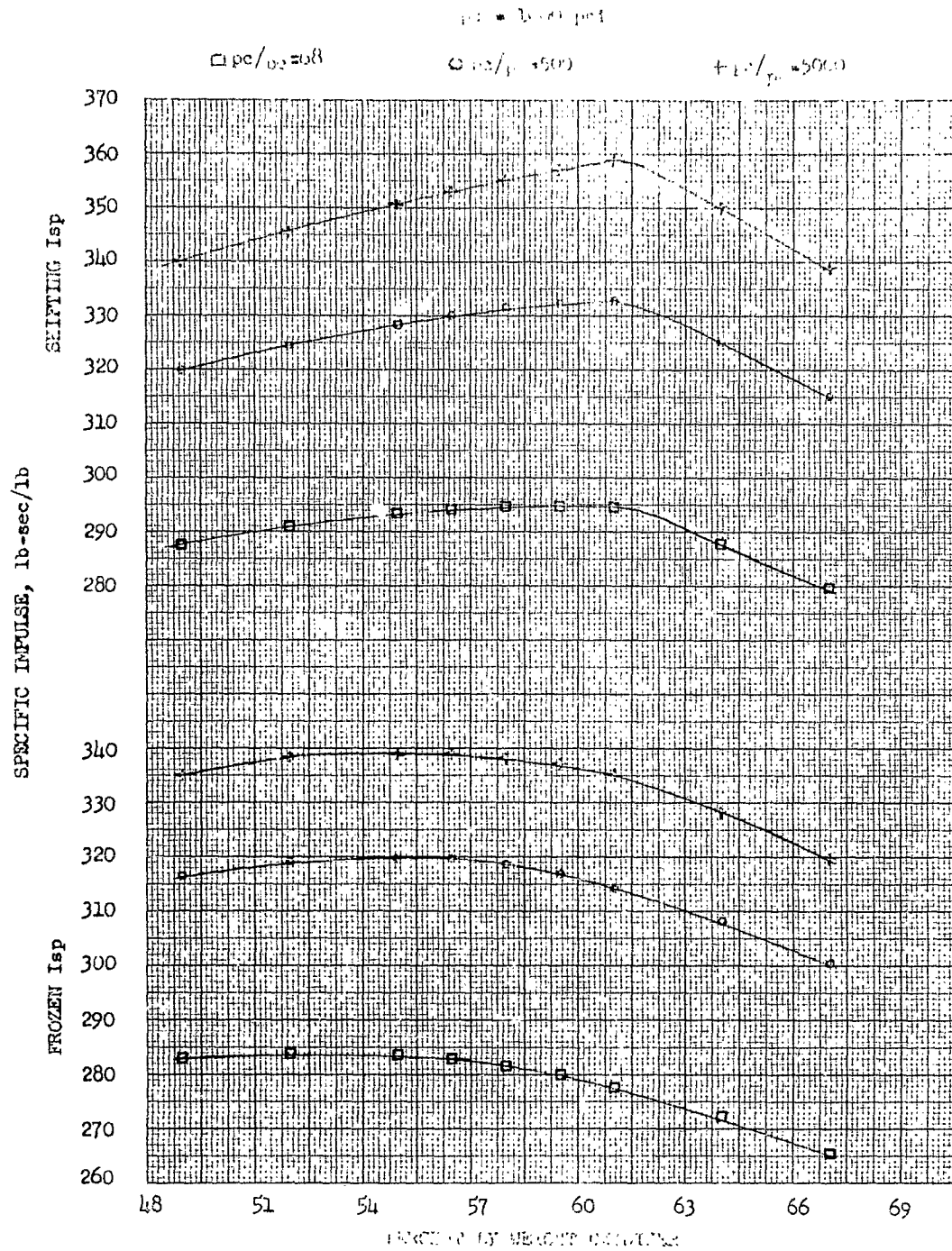


HYDRAZINE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 50

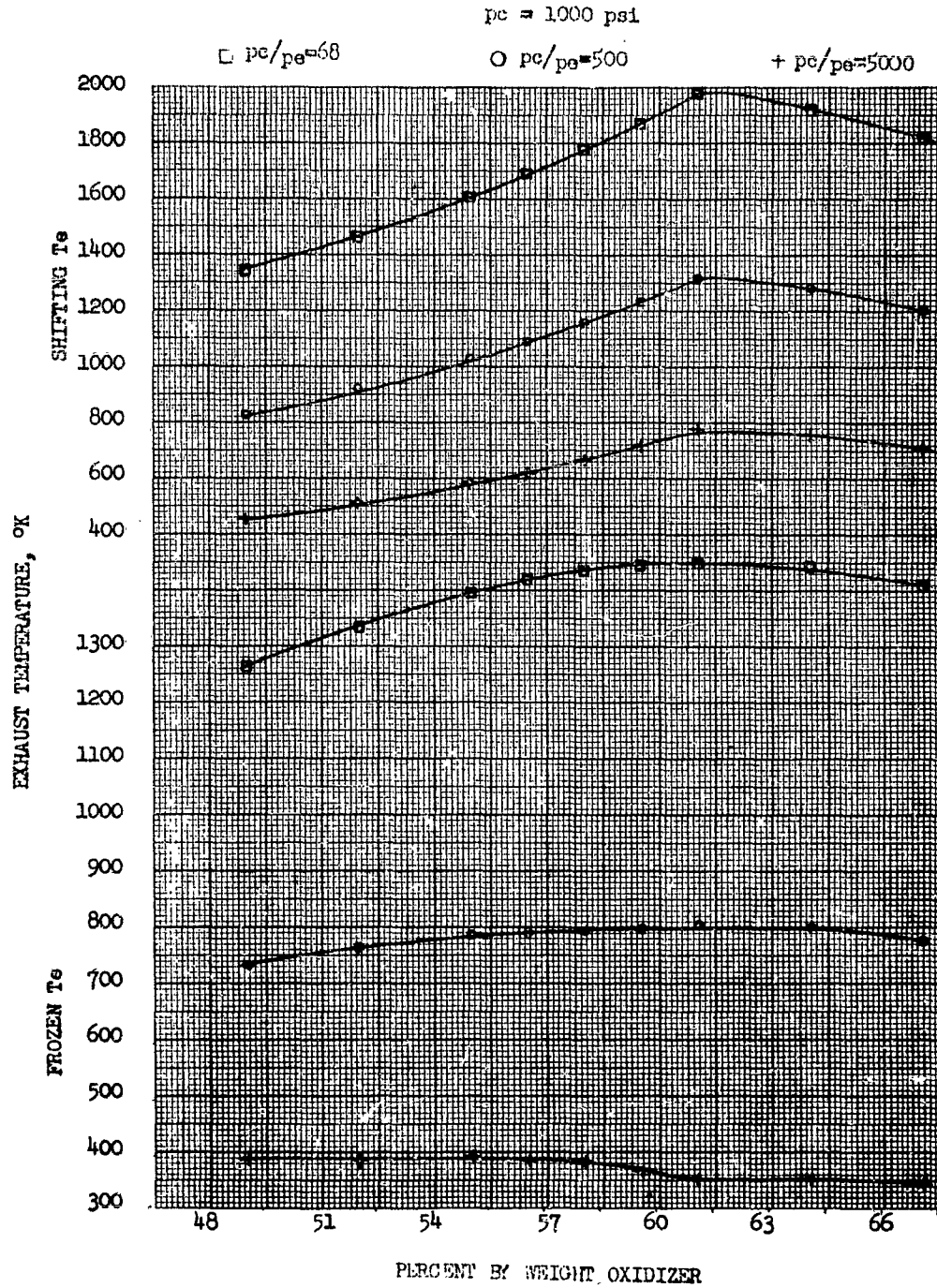




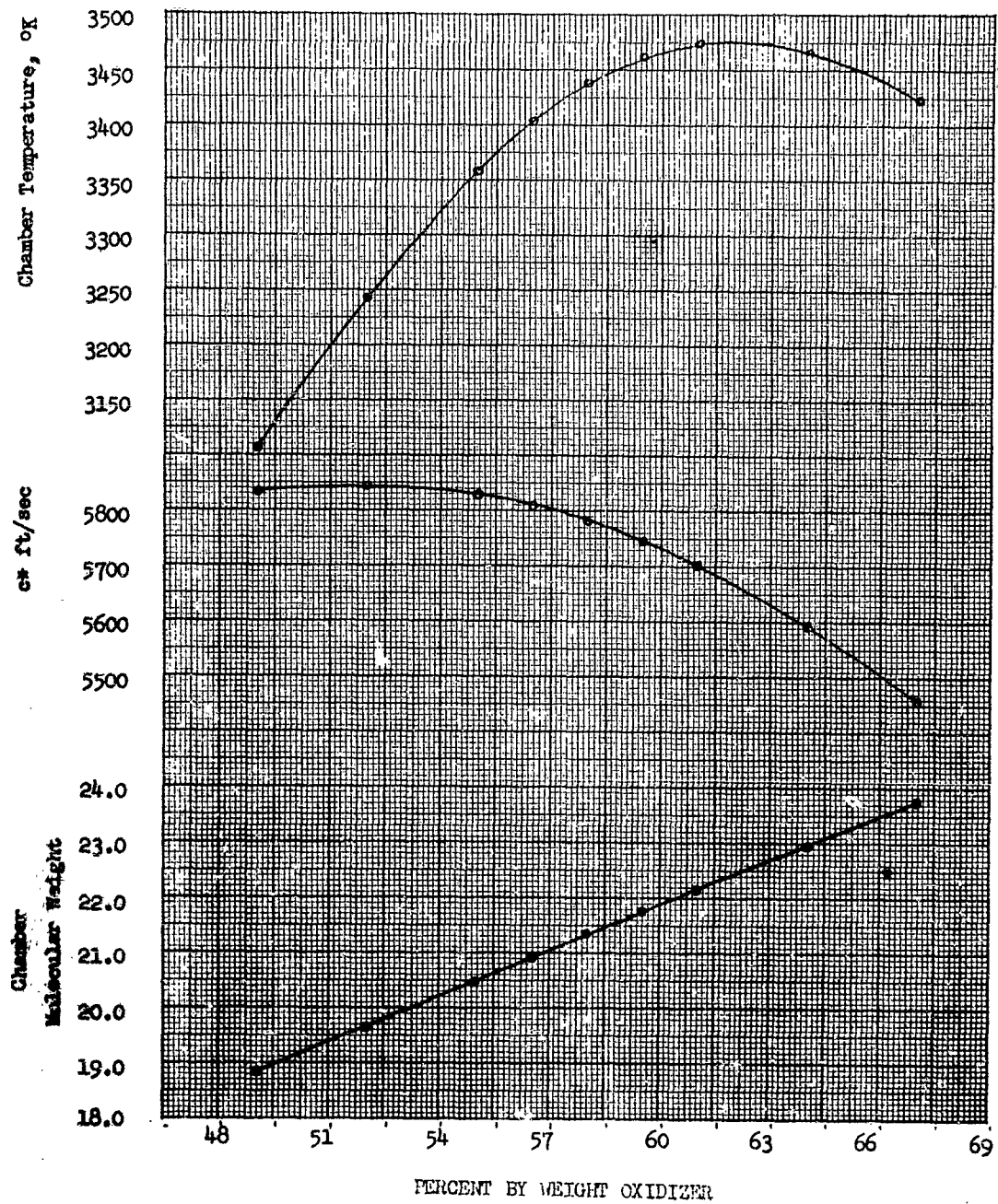
HYDRAZINE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 52



HYDRAZINE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 53



HYDRAZINE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 54



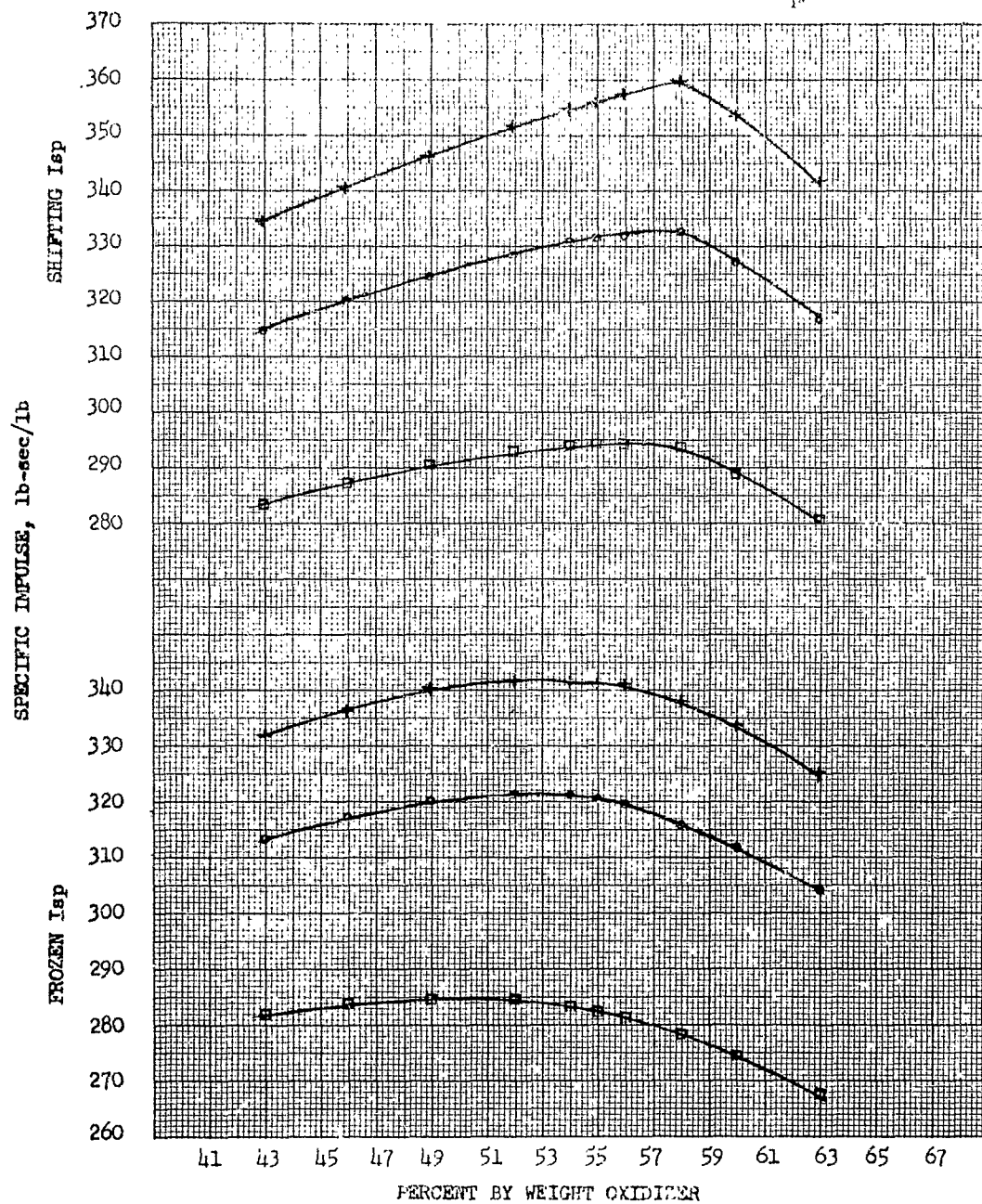
HYDROGEN - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 55

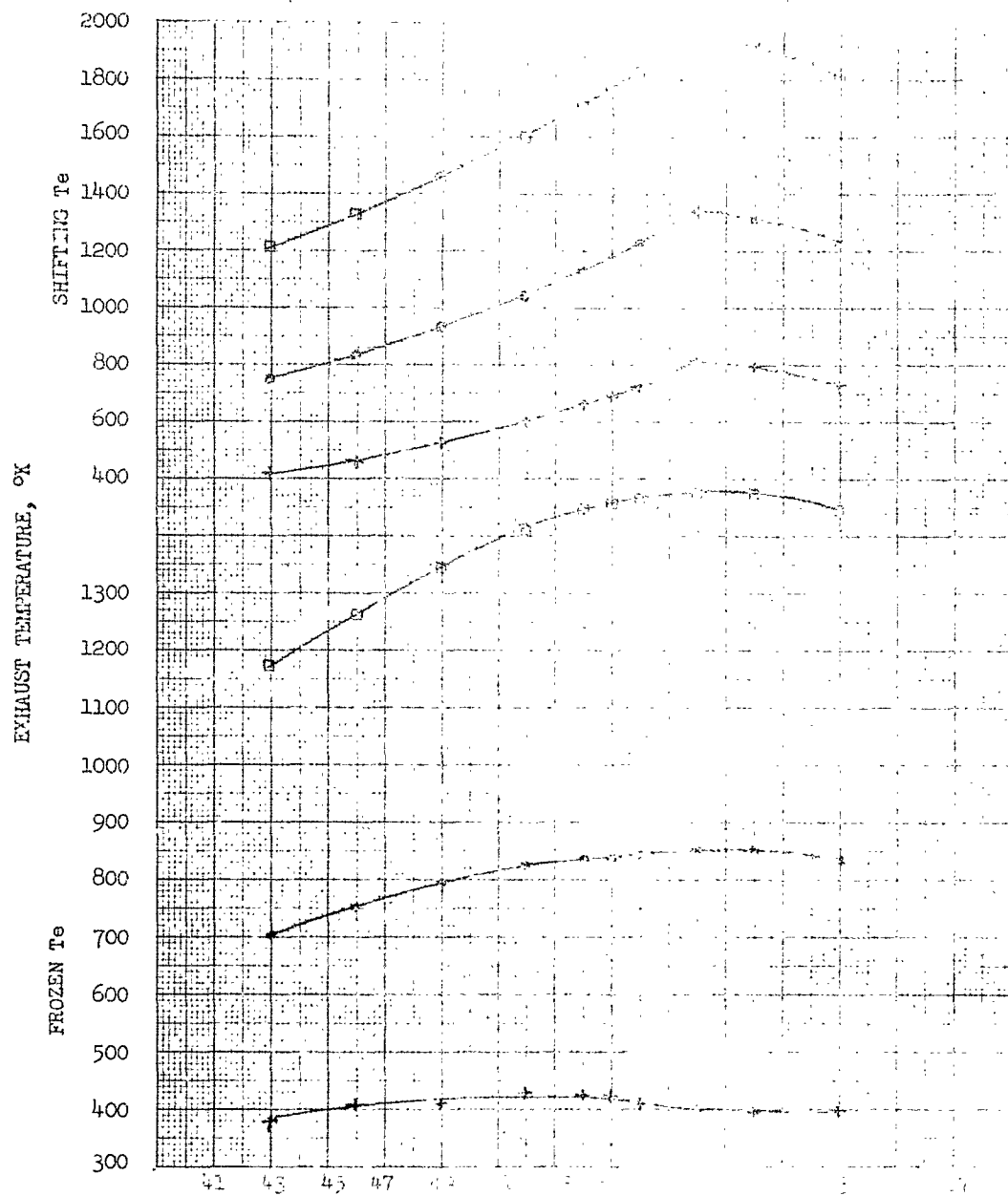
• 1000

$C_{sp}/P_{sp} = 20.3$

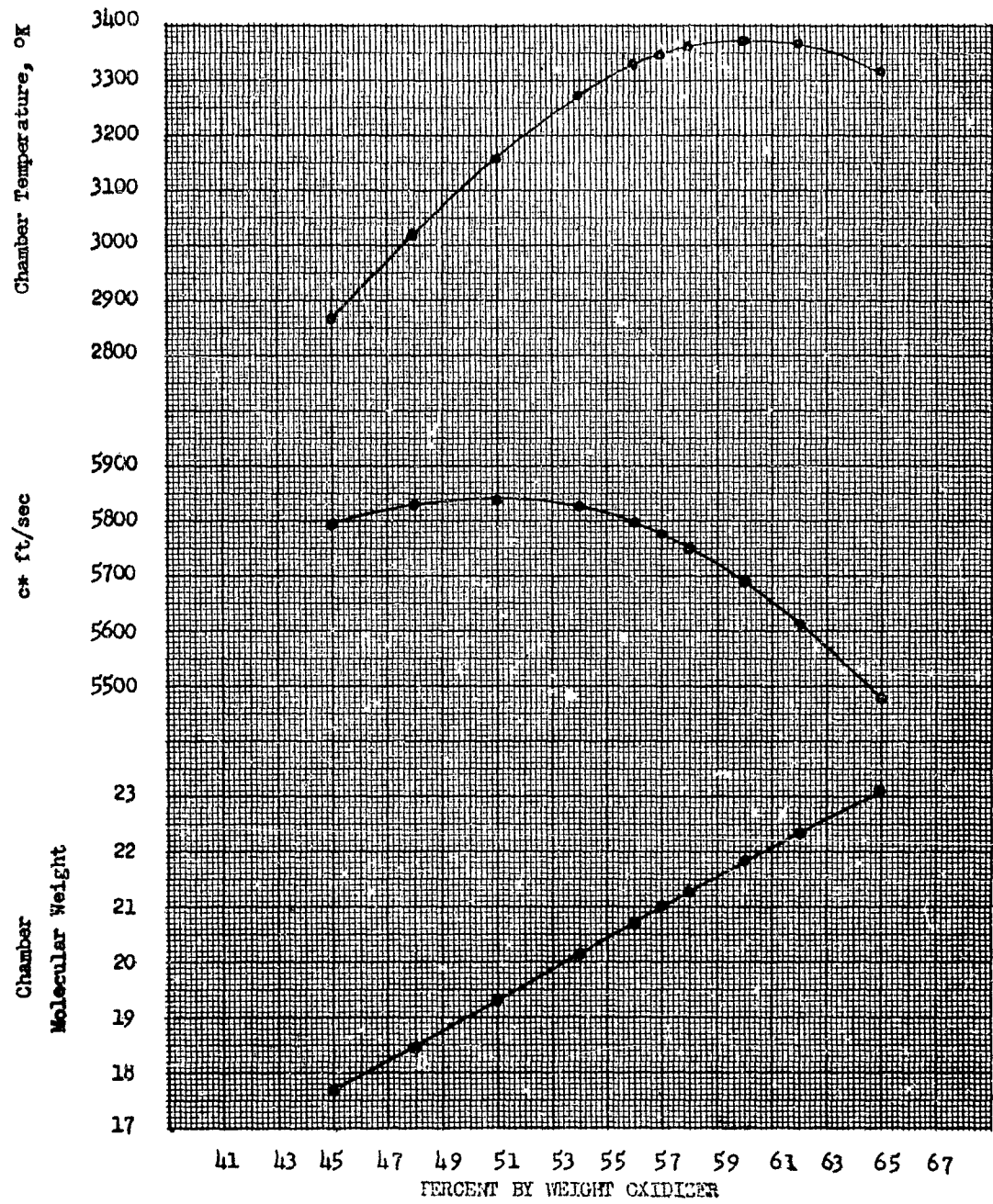
$C_{sp}/P_{sp} = 500$

$C_{sp}/P_{sp} = 500.0$





HYDRAZINE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 57



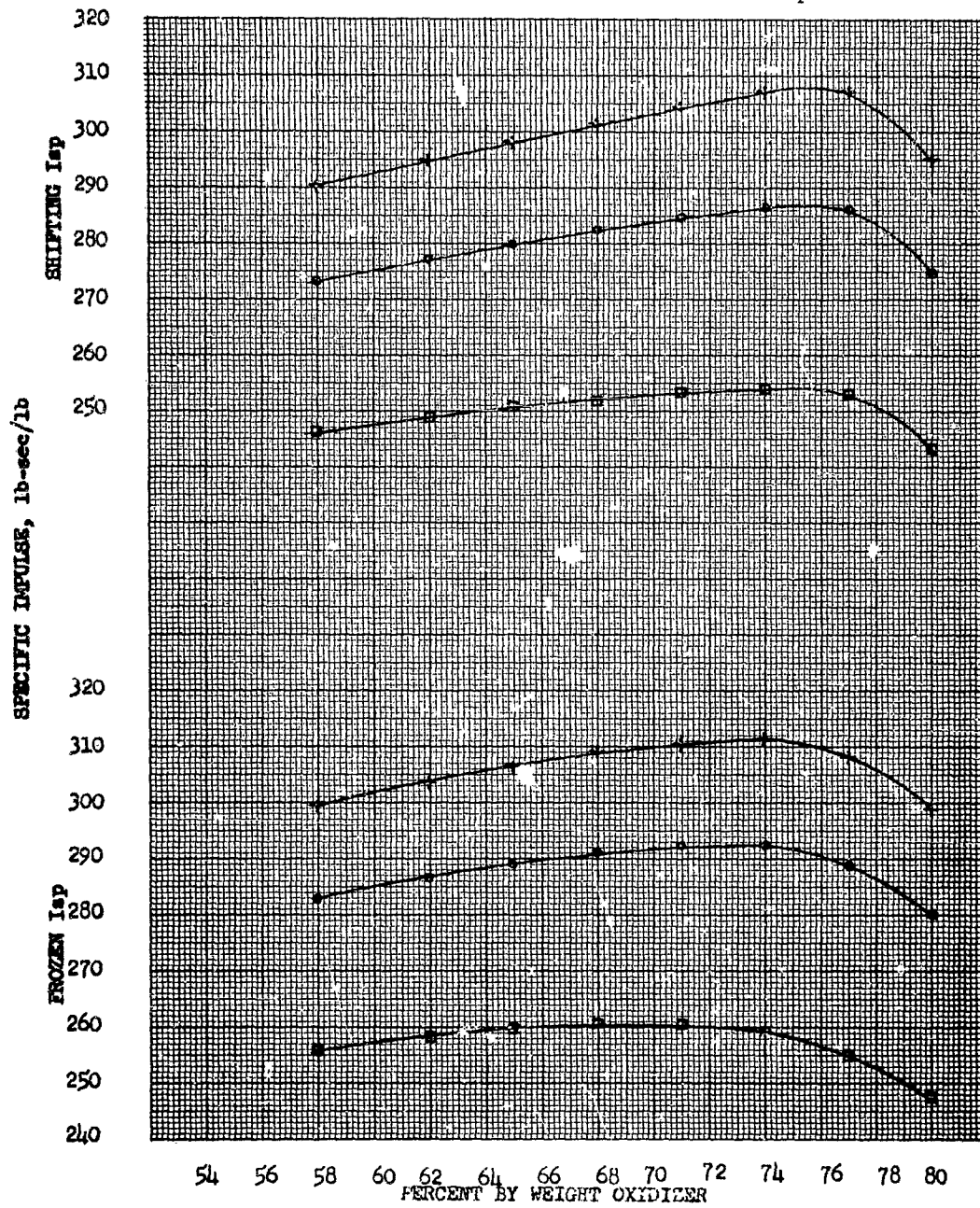
HYDRAZINE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 58

$p_c = 1000 \text{ psi}$

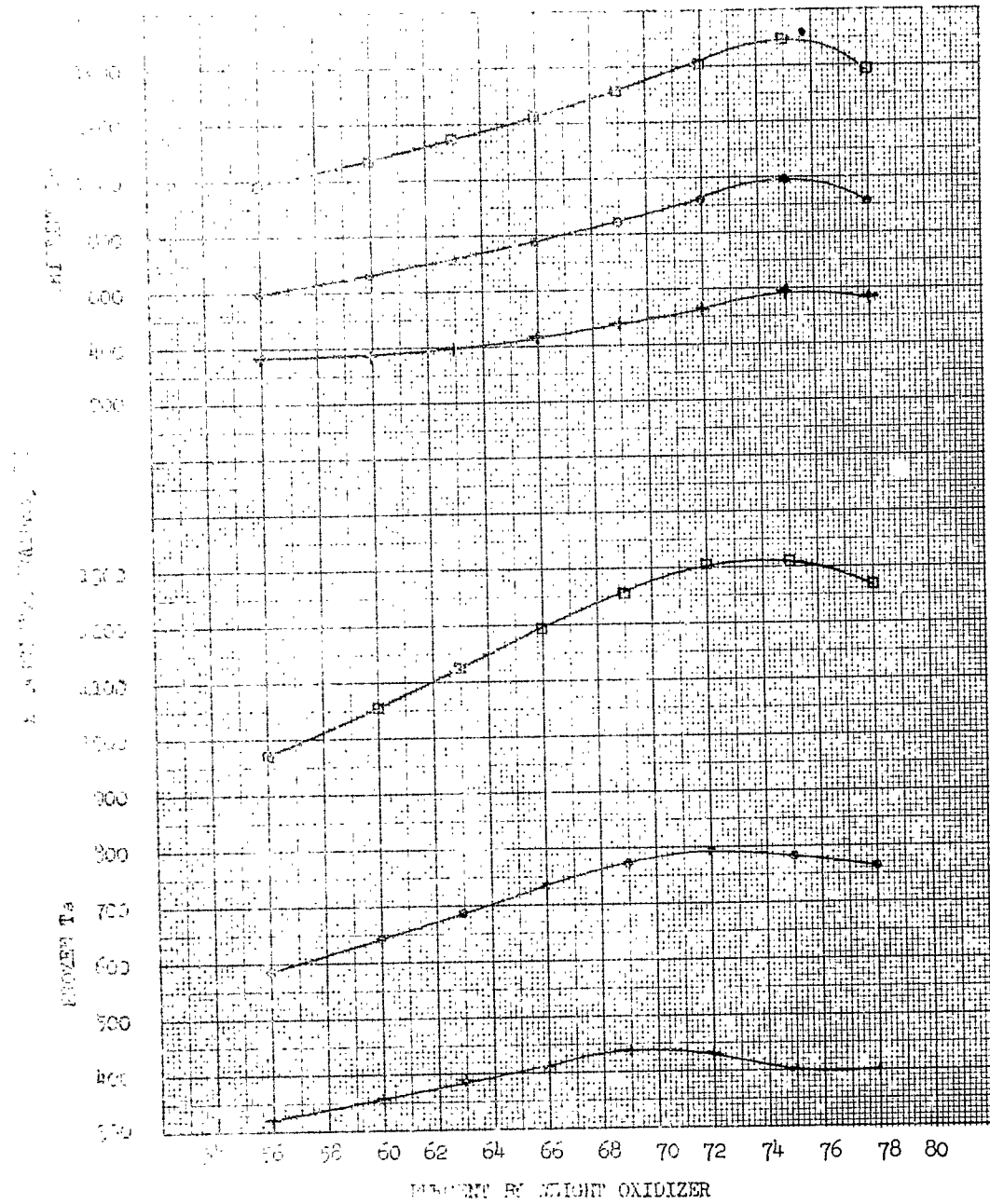
$\square p_c/p_e = 68$

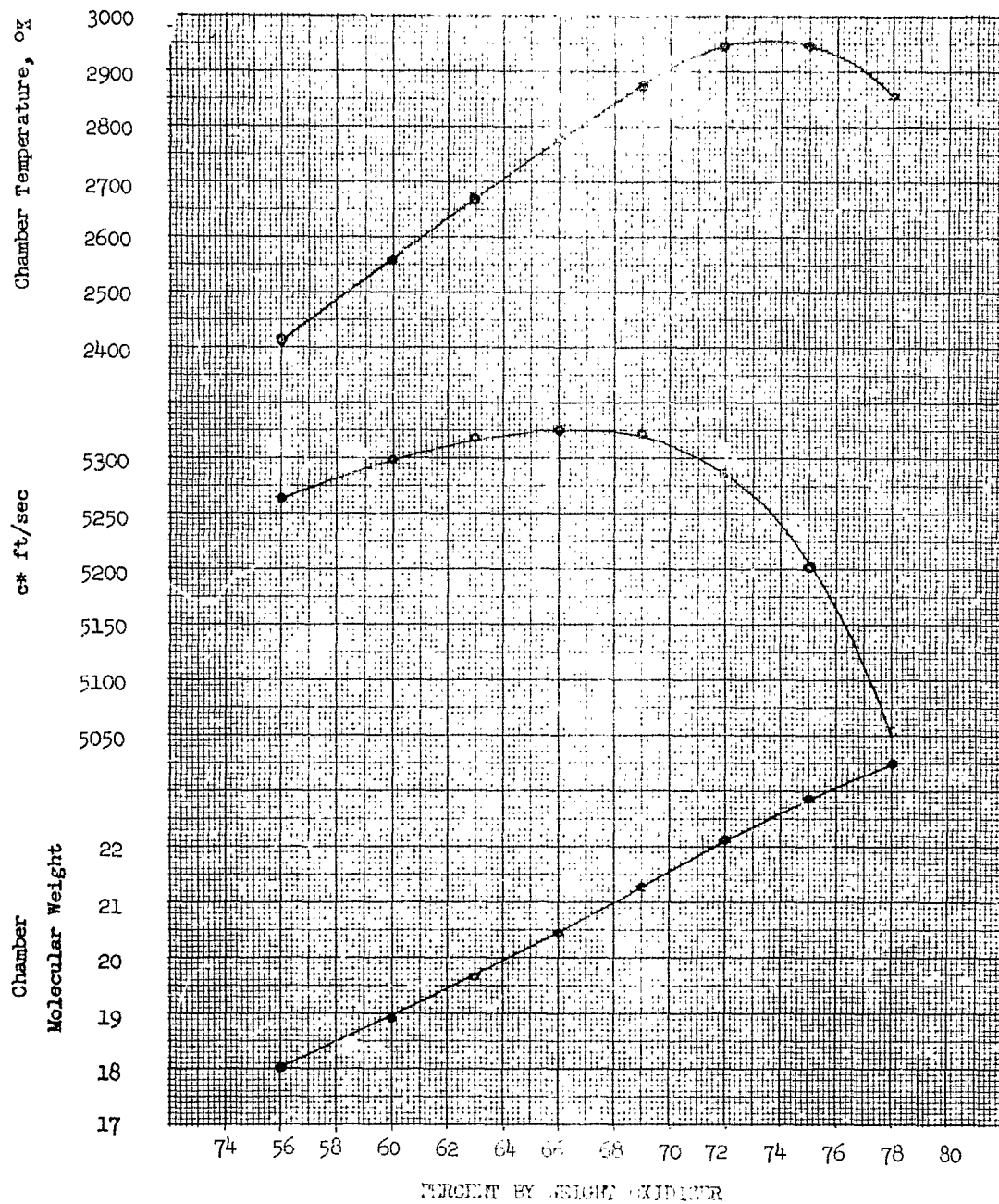
$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$



+ 20/100 (25/100)





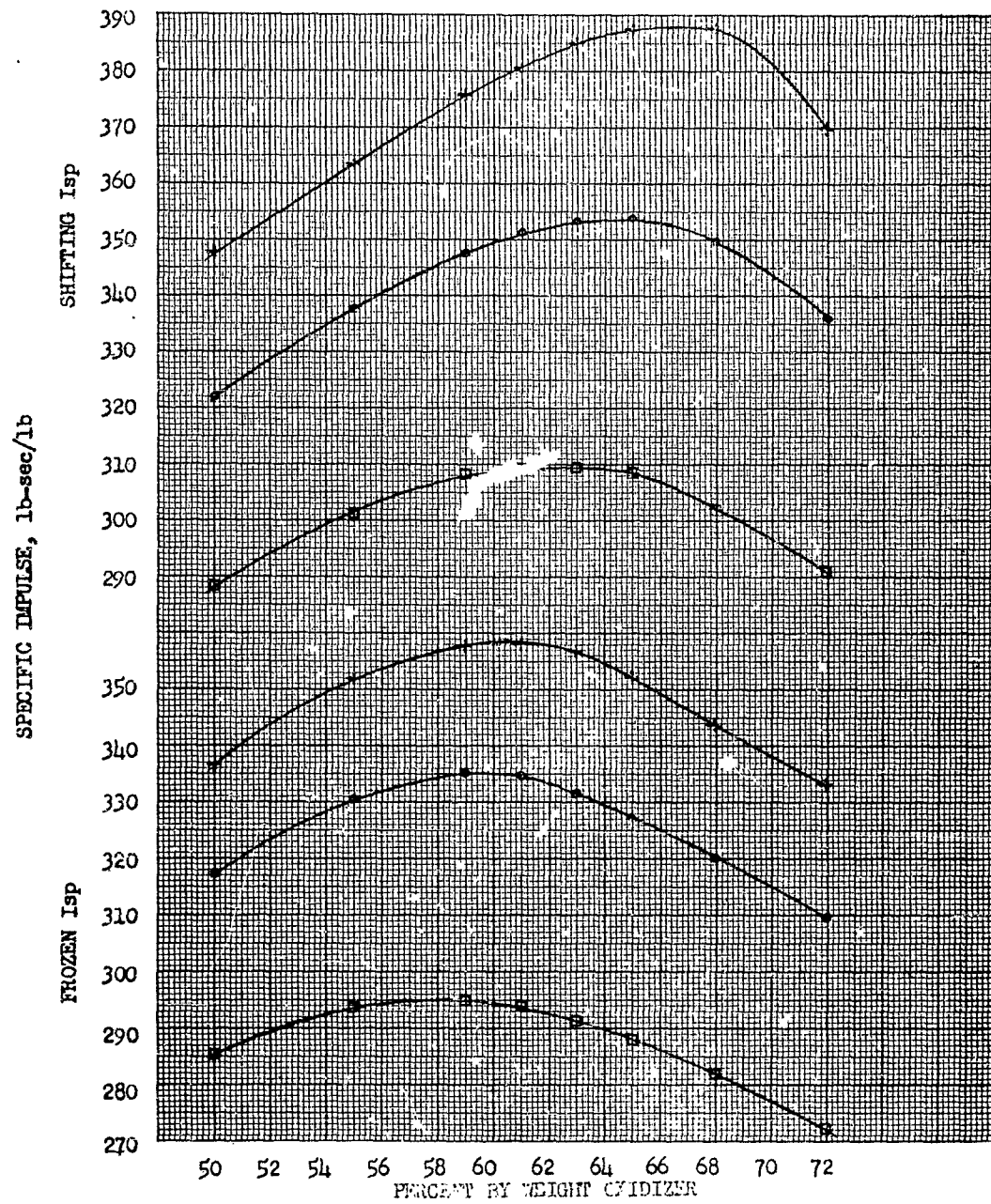
UDMH - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 61

$p_c = 1000 \text{ psi}$

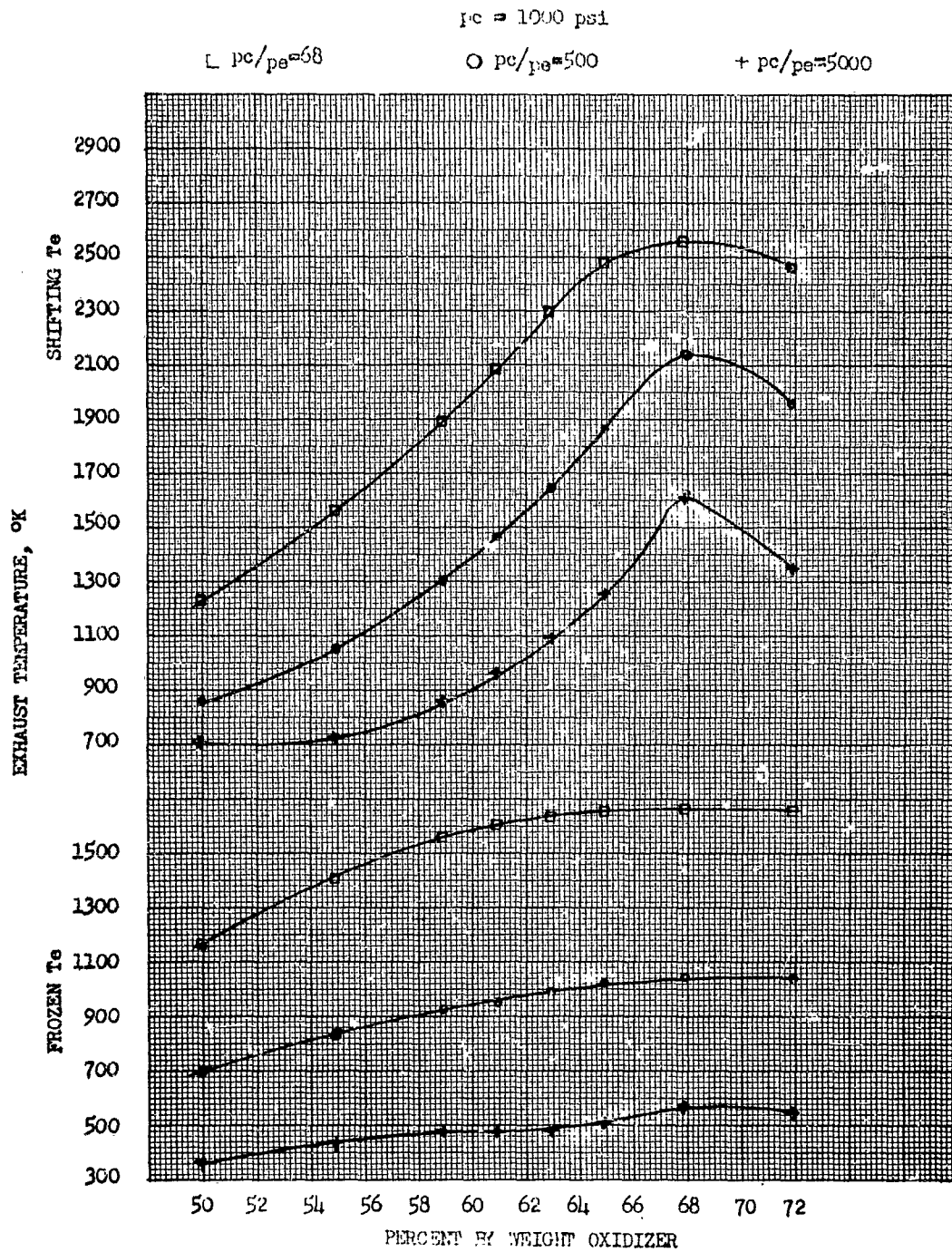
$\square p_c/p_a = 68$

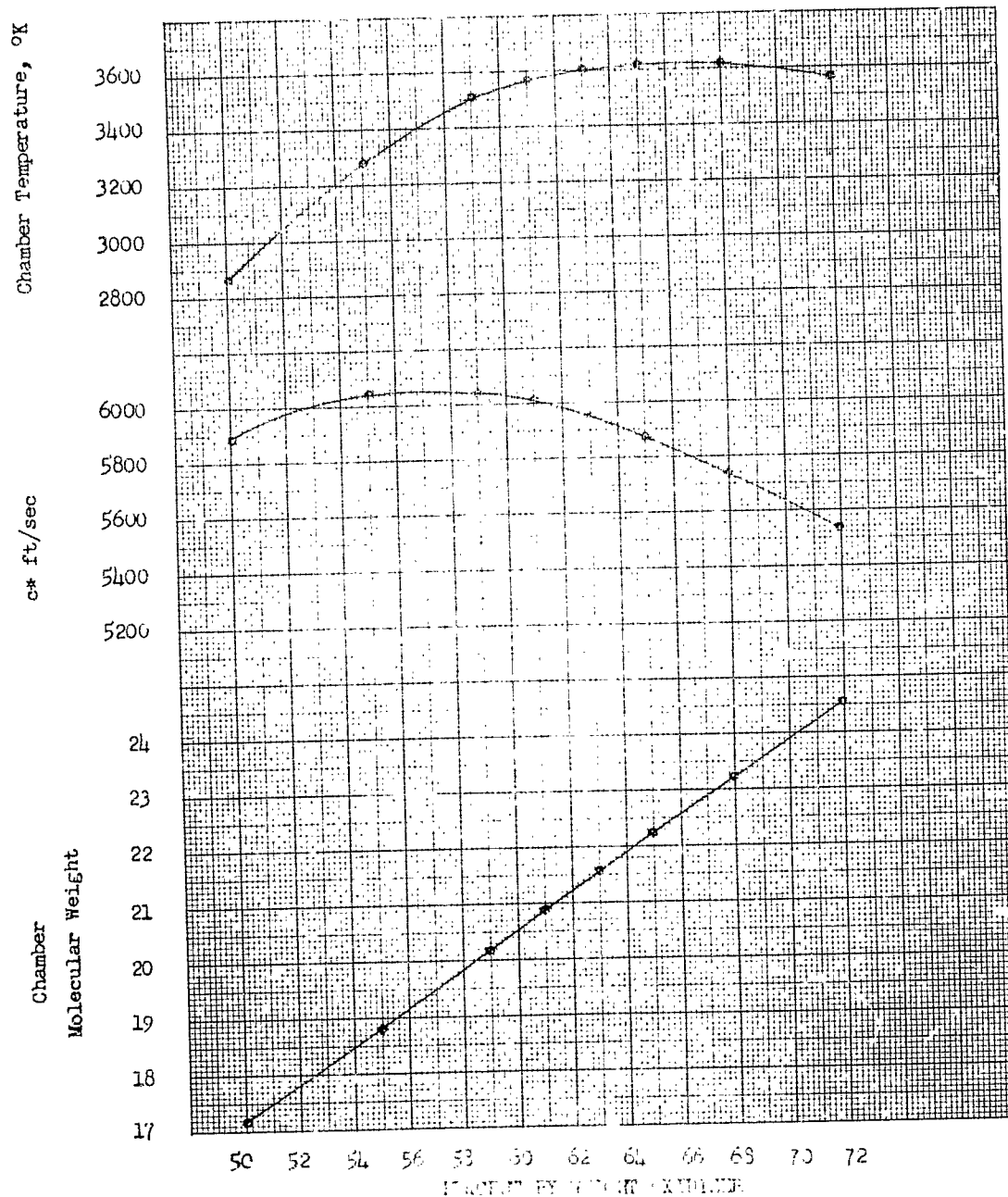
$\circ p_c/p_a = 500$

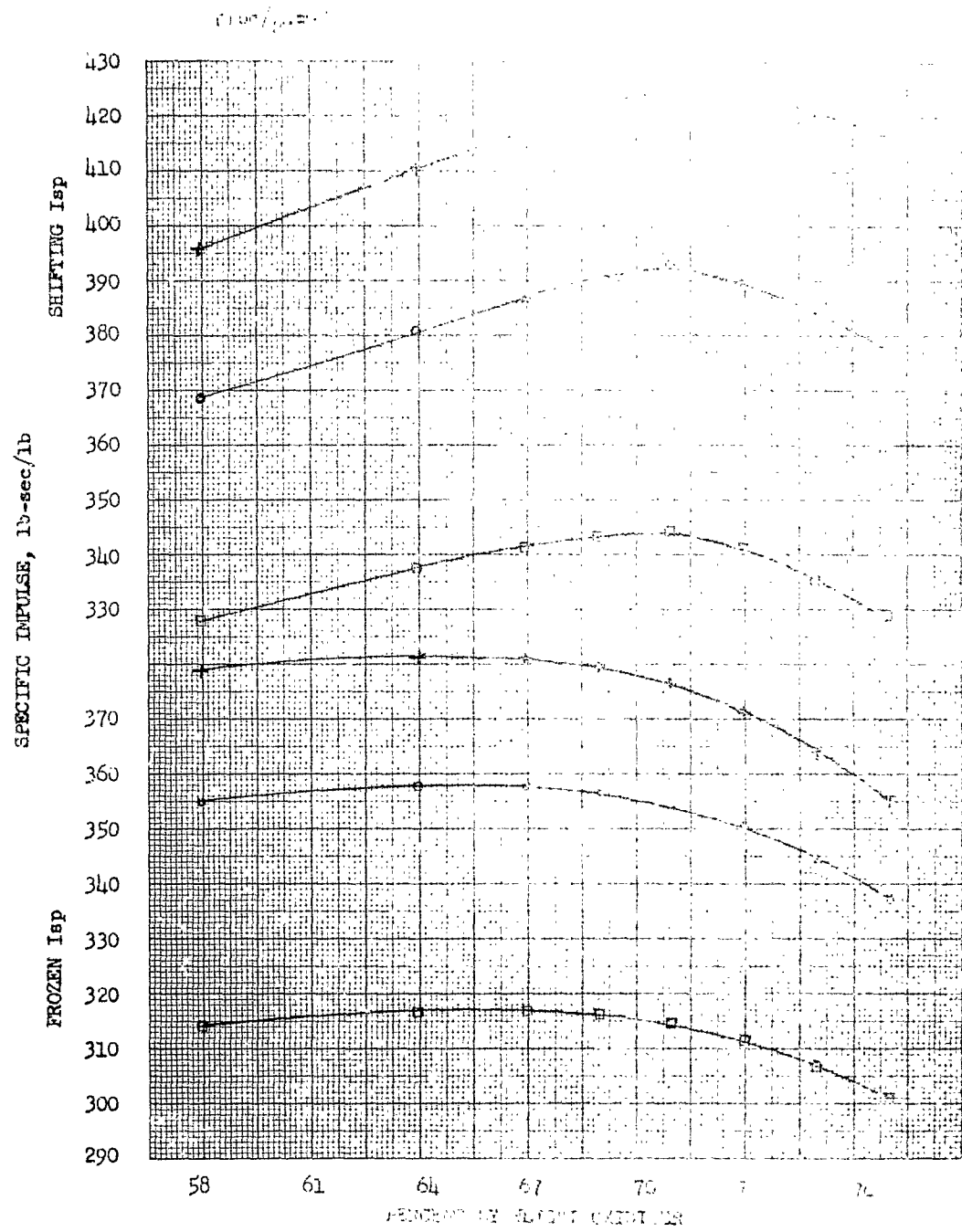
$+ p_c/p_a = 5000$



UDMH - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 62







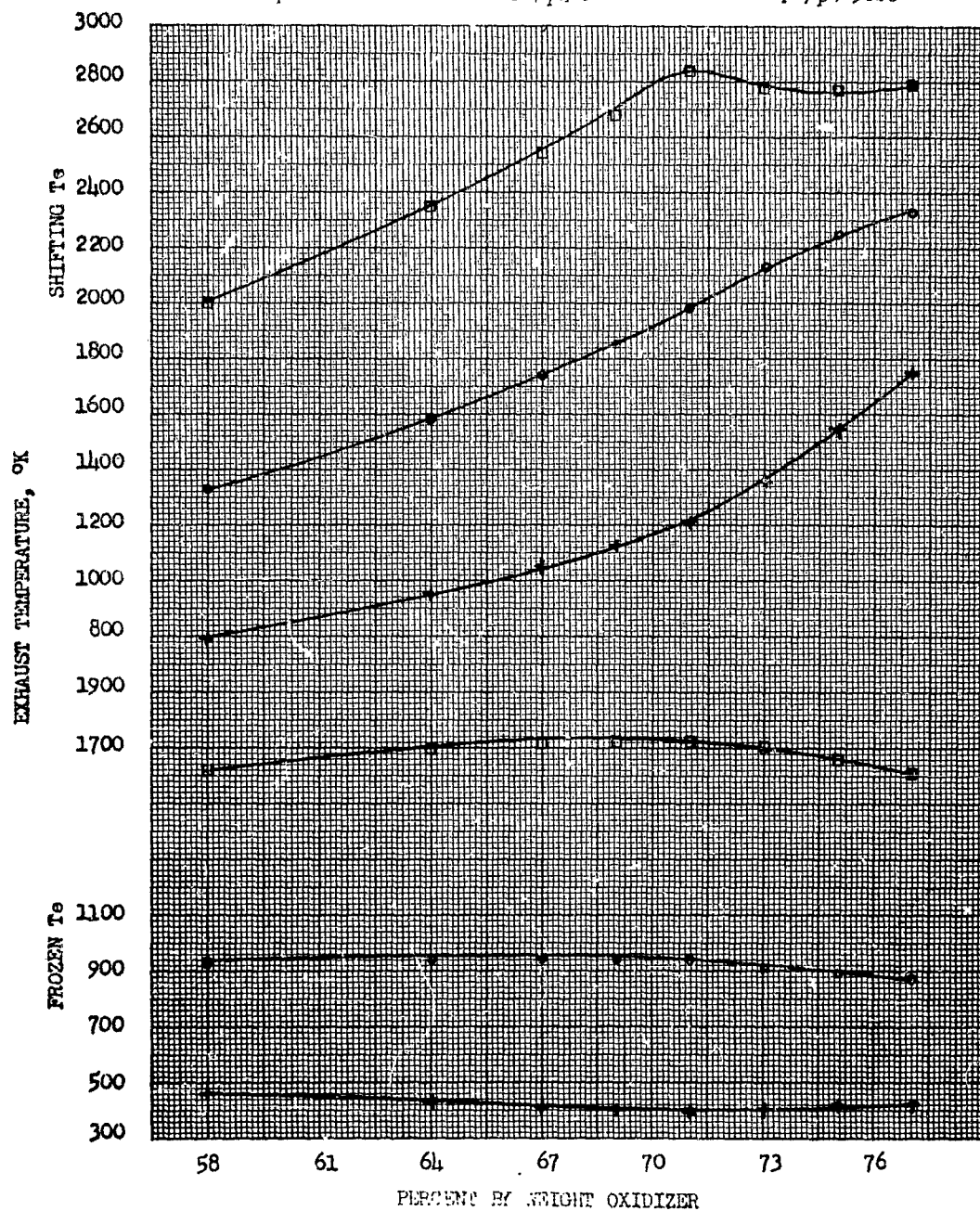
UDMH - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 65

$p_c = 1000 \text{ psi}$

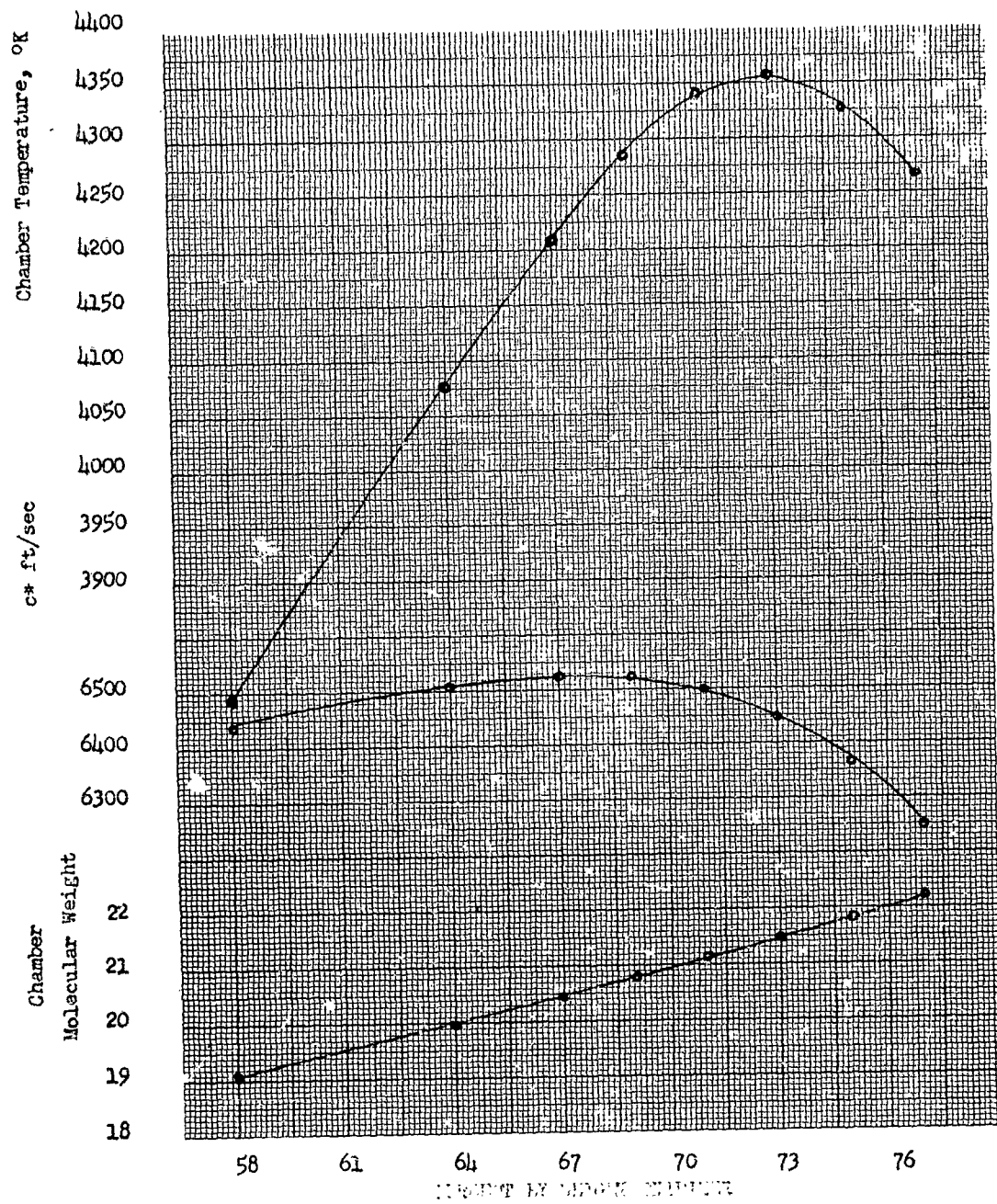
$\square p_c/p_a = 68$

$\circ p_c/p_a = 500$

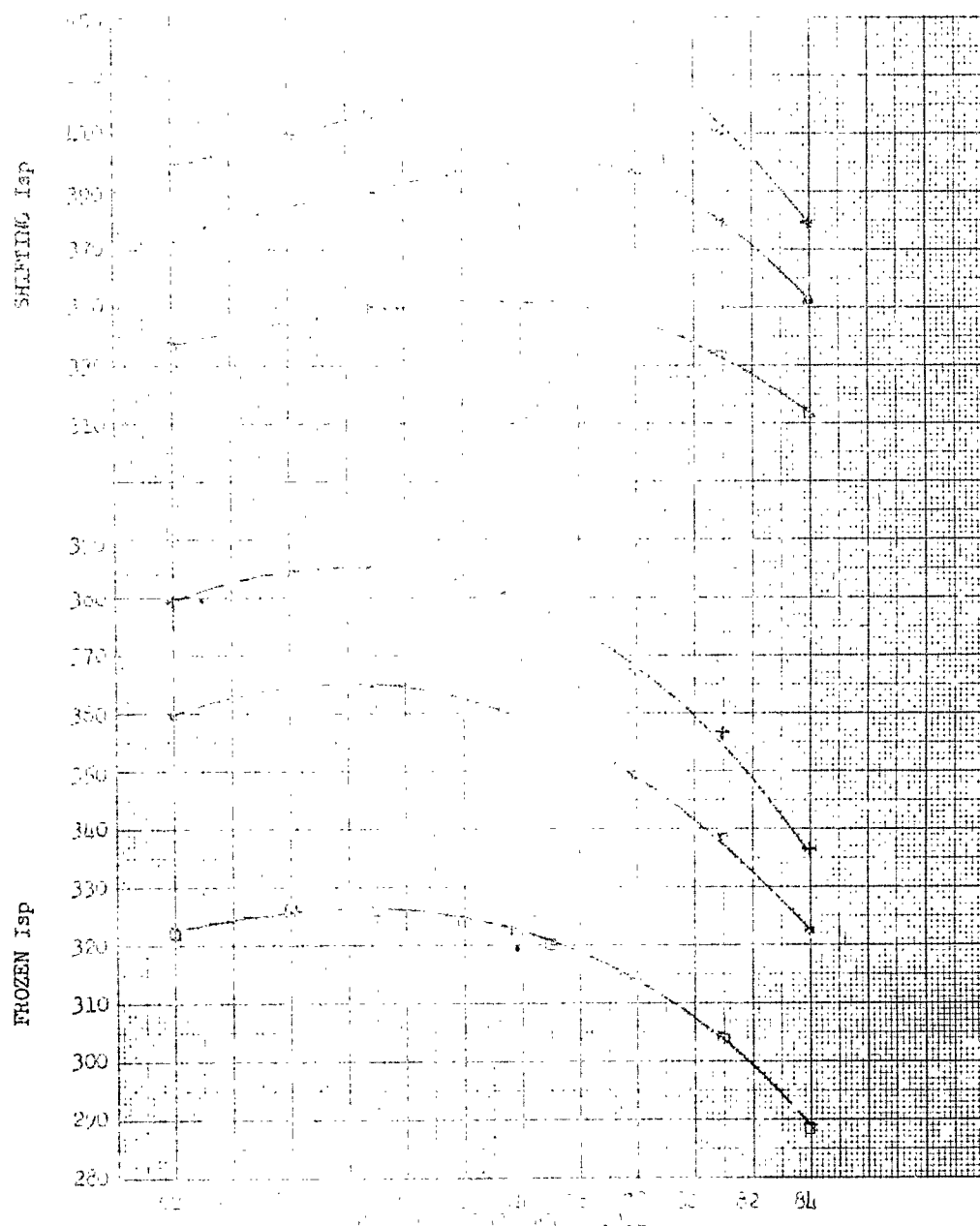
$+ p_c/p_a = 5000$



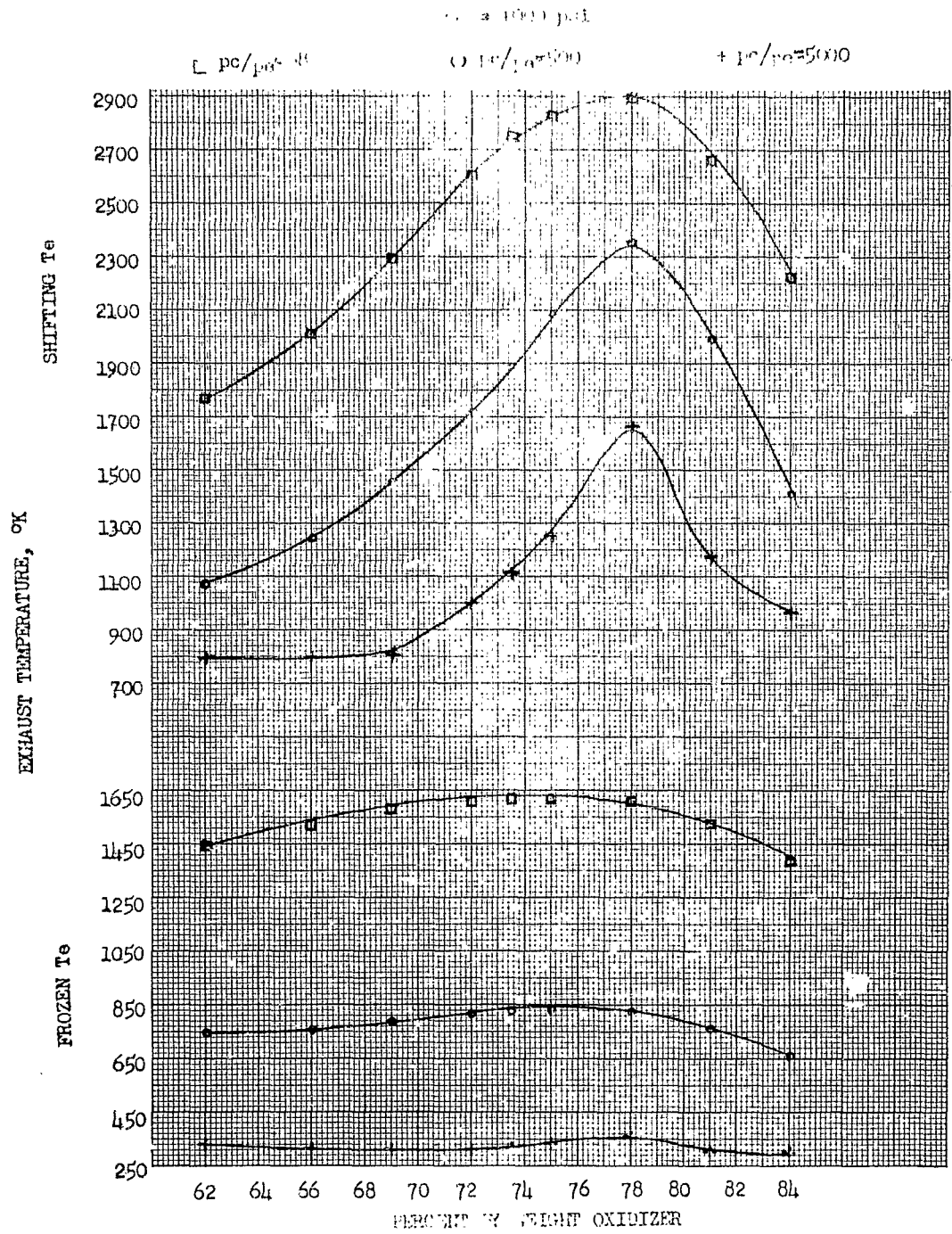
UDMH - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 66



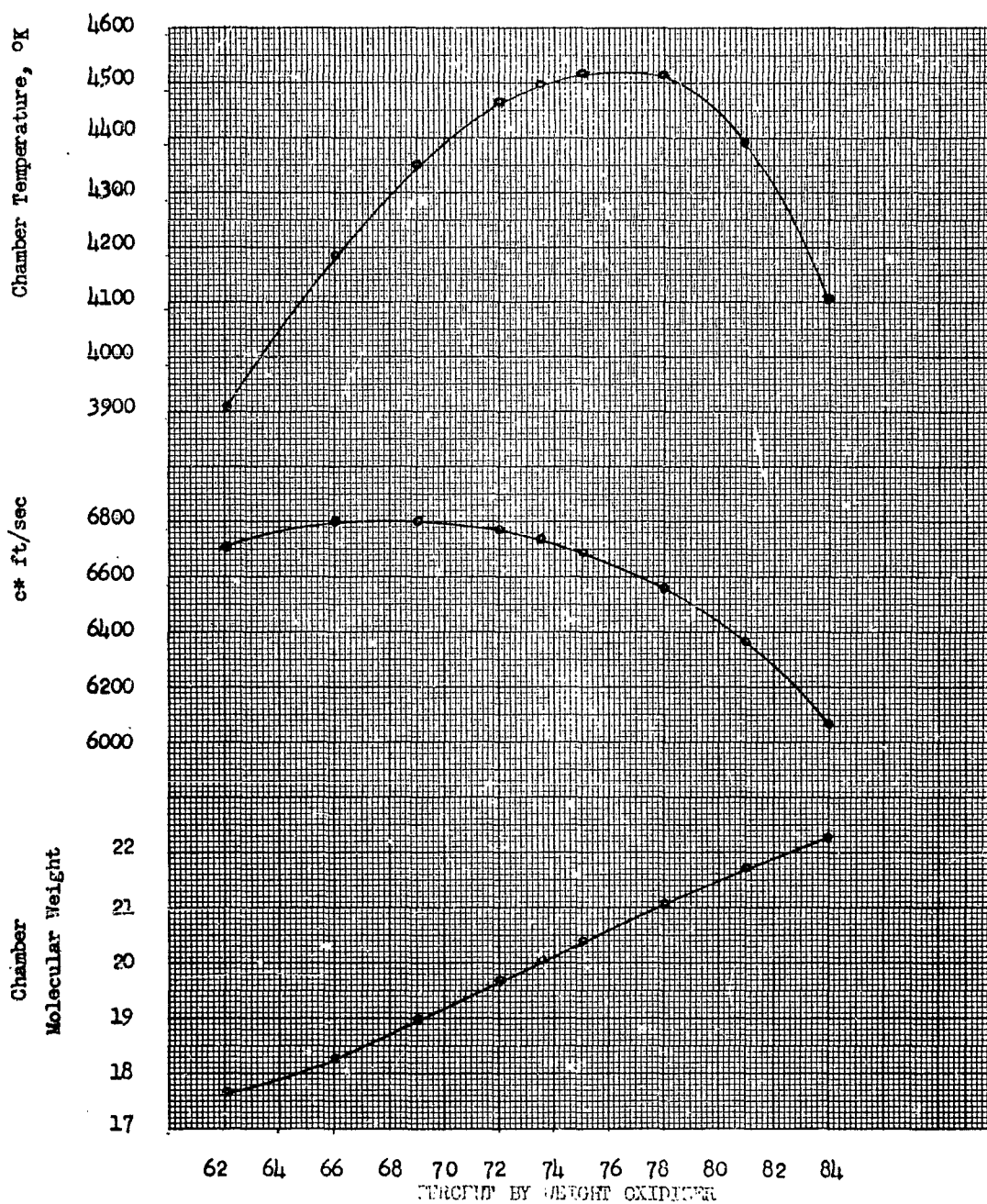
SPECIFIC IMPULSE, lb-sec/lb



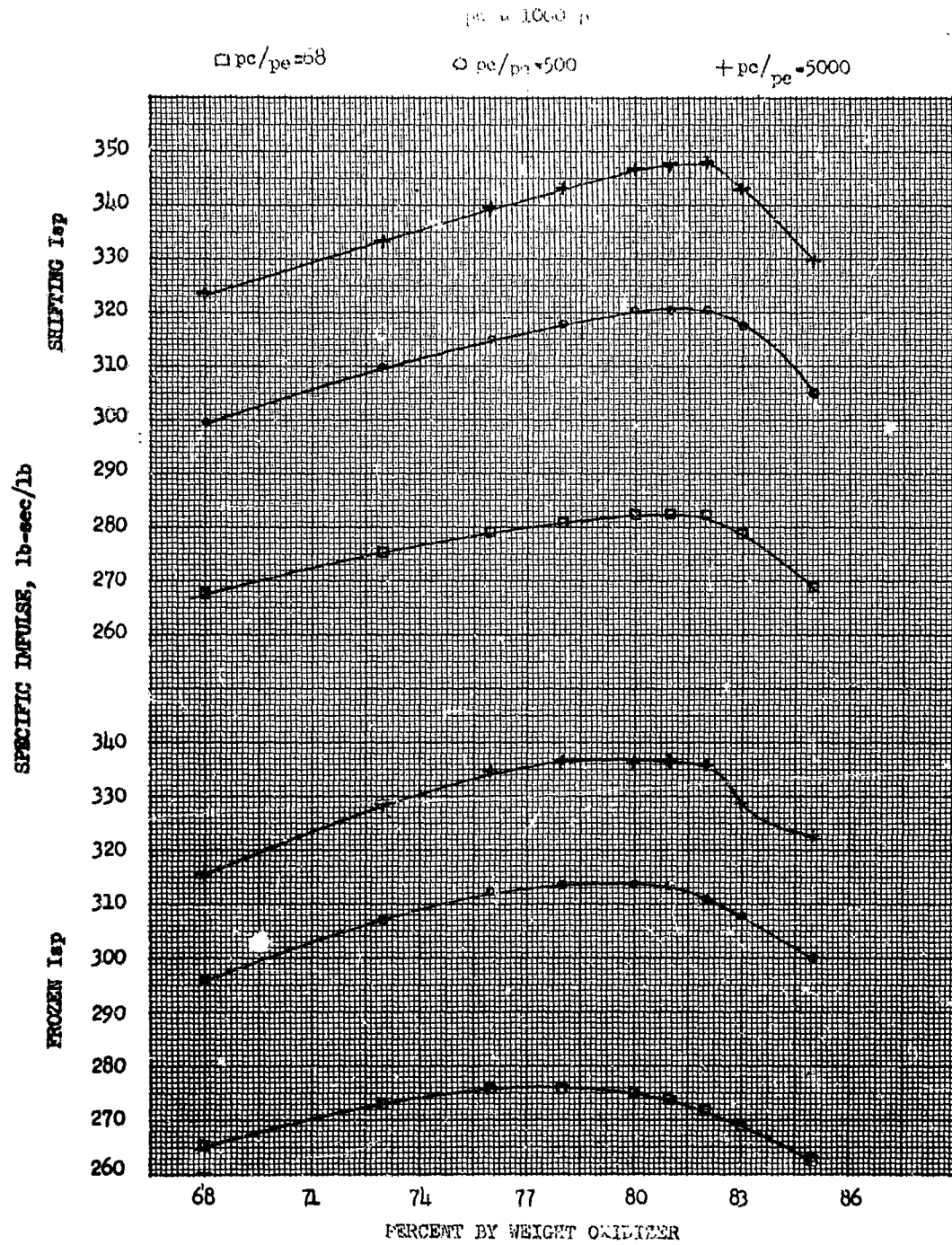
UD-1H - OXYGEN DIFFUSION PERFORMANCE CURVES - FIGURE 68



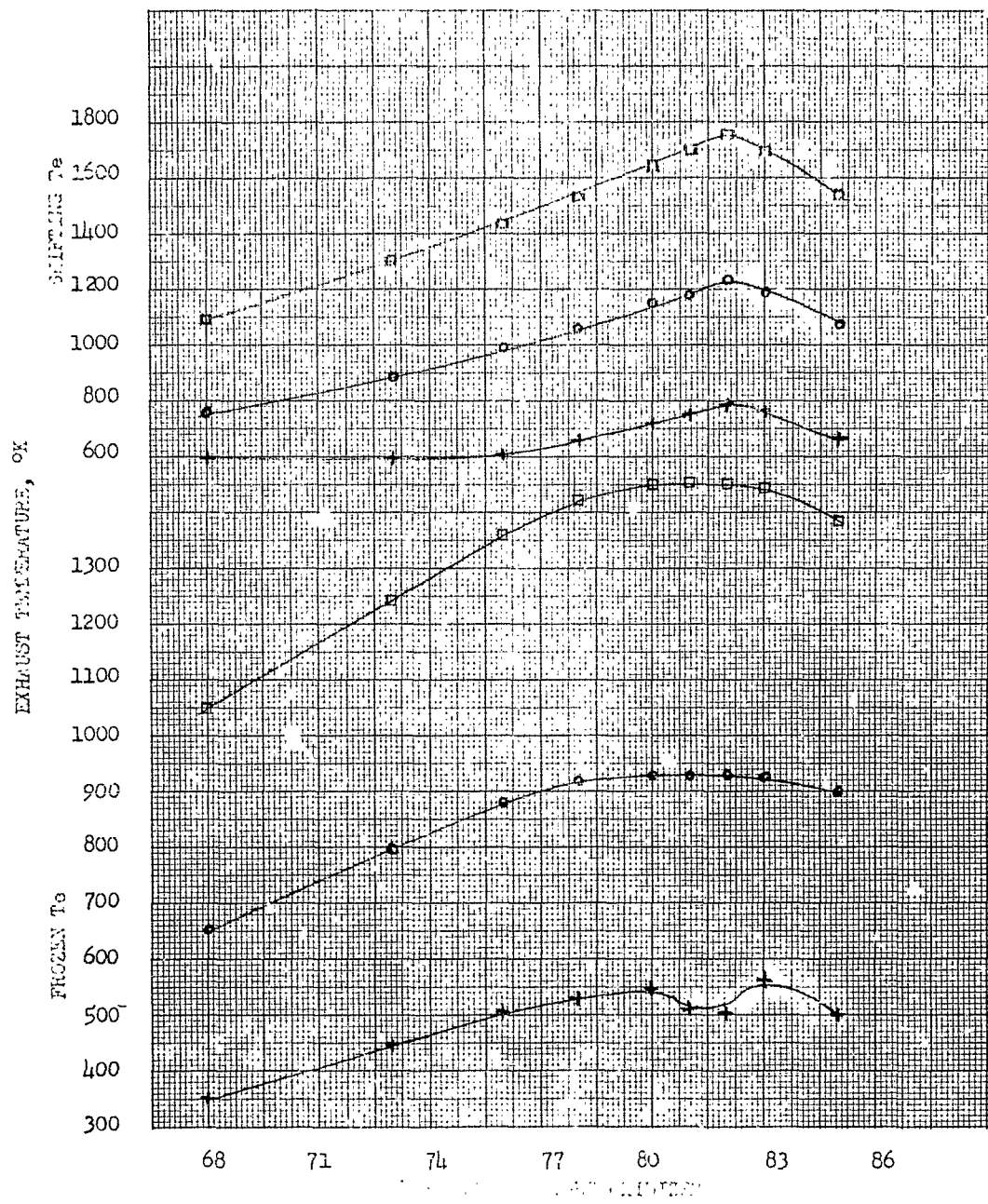
UDMH - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 69



UDMH - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 70



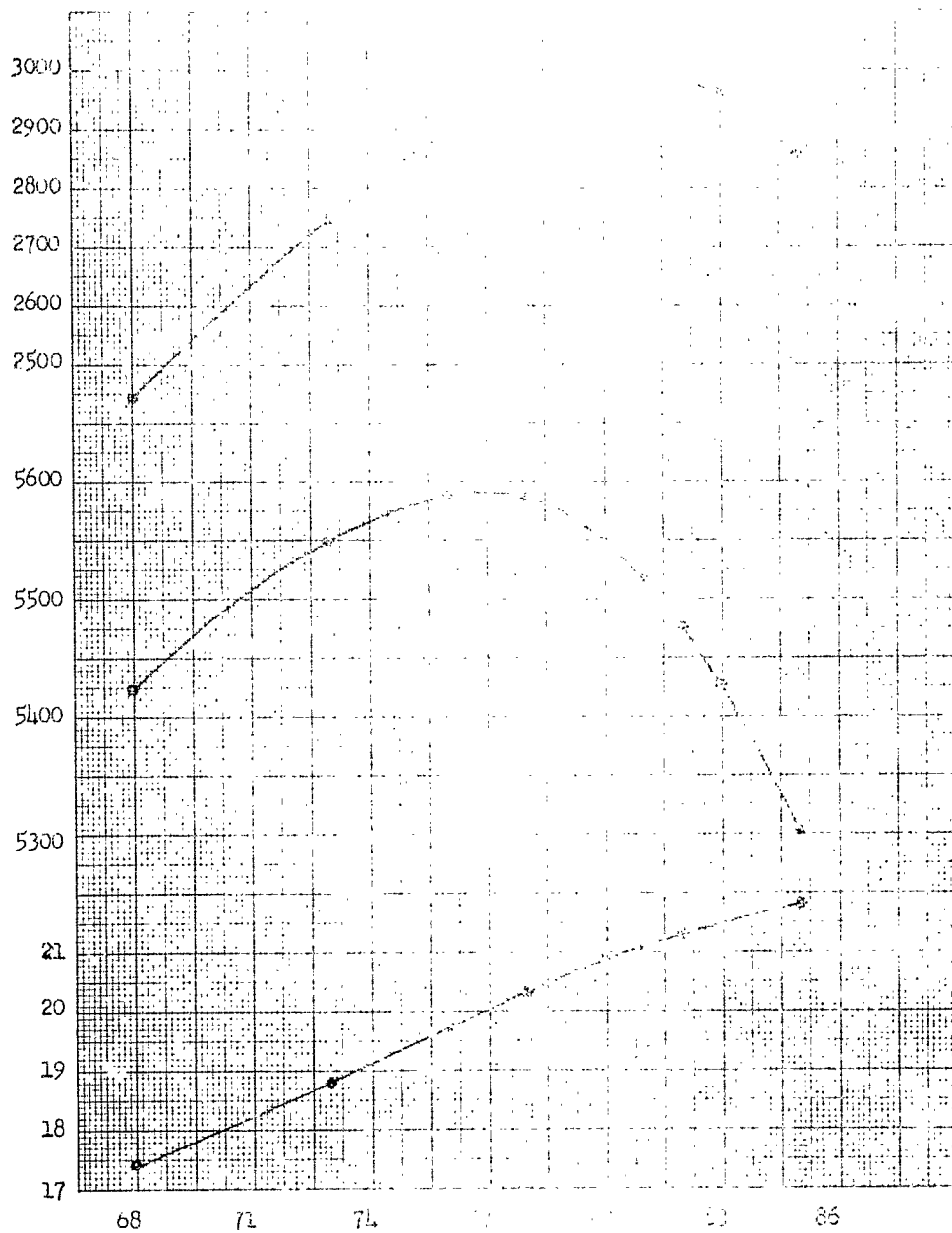
ODMH - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 71



Chamber Temperature, °K

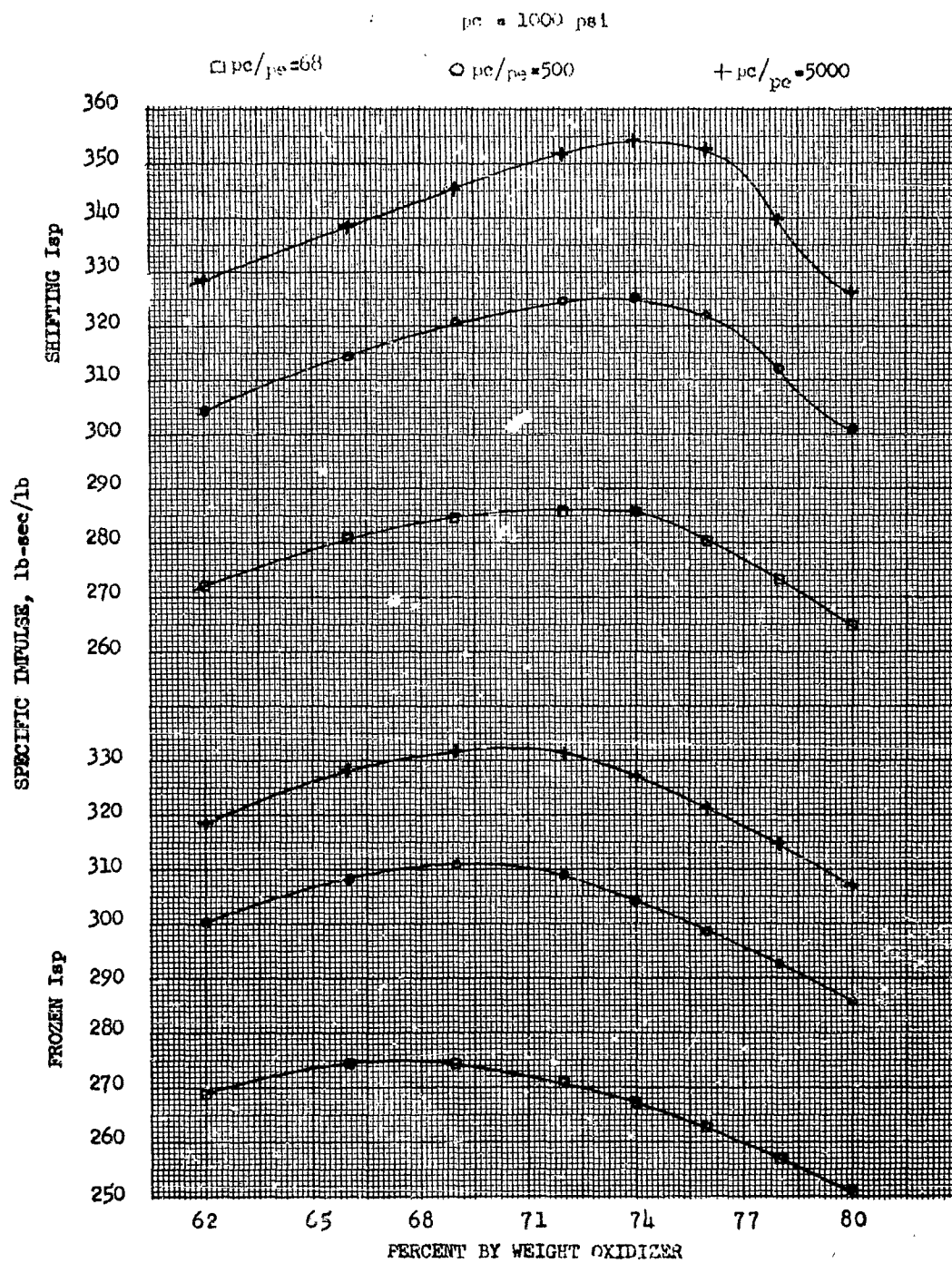
c* ft/sec

Chamber
Molecular Weight

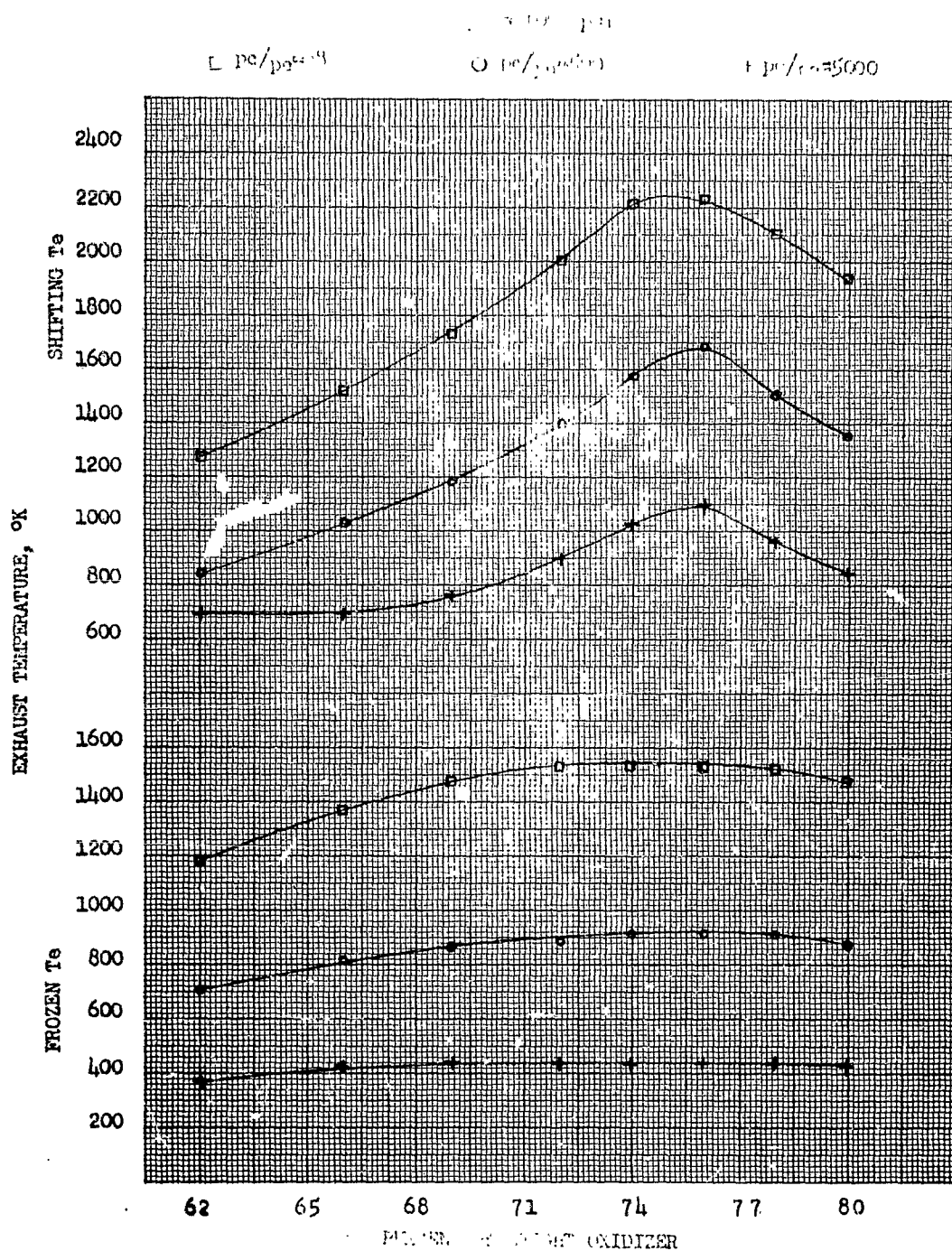


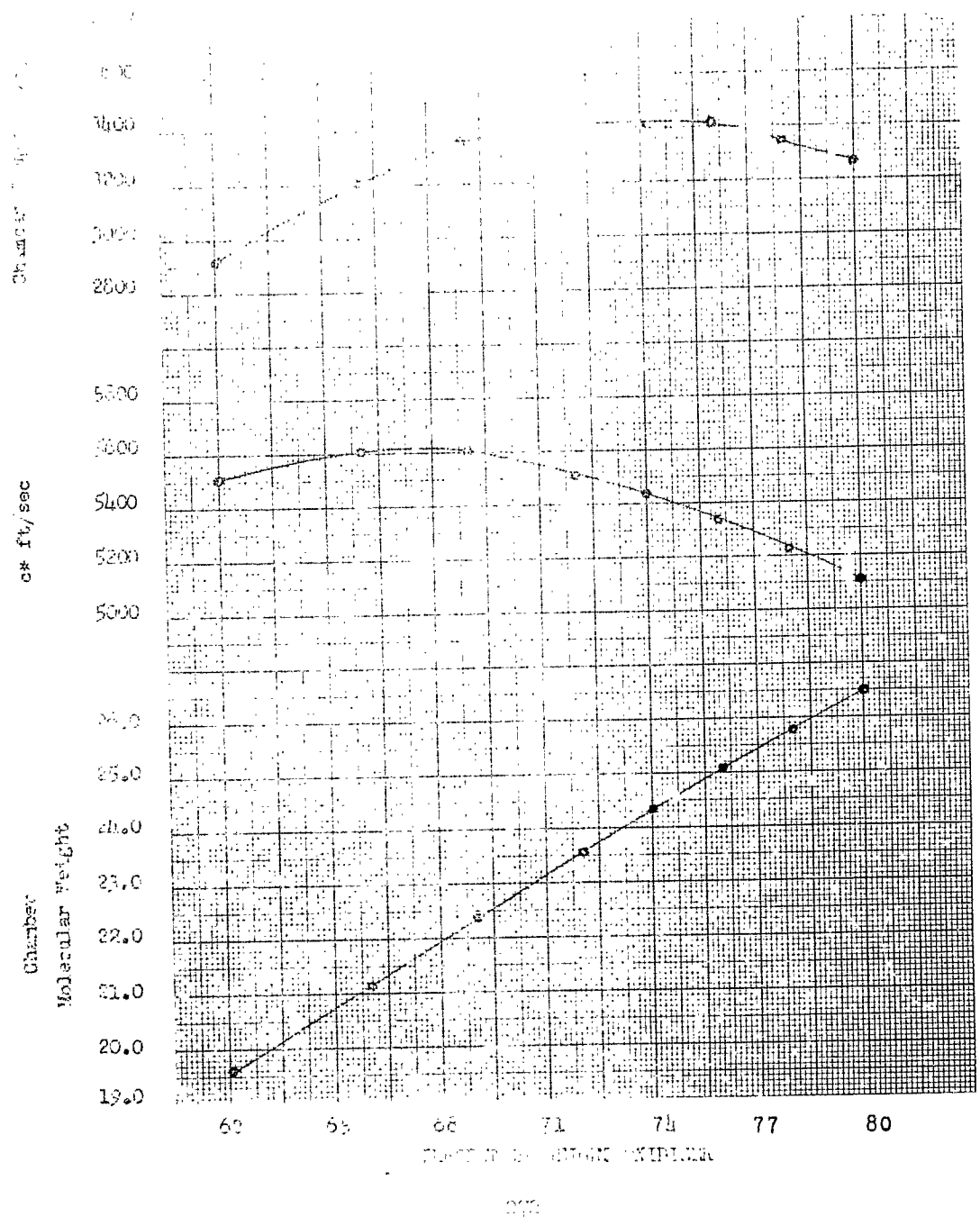
CHAMBER TEMPERATURE, °K

UDMH - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 73



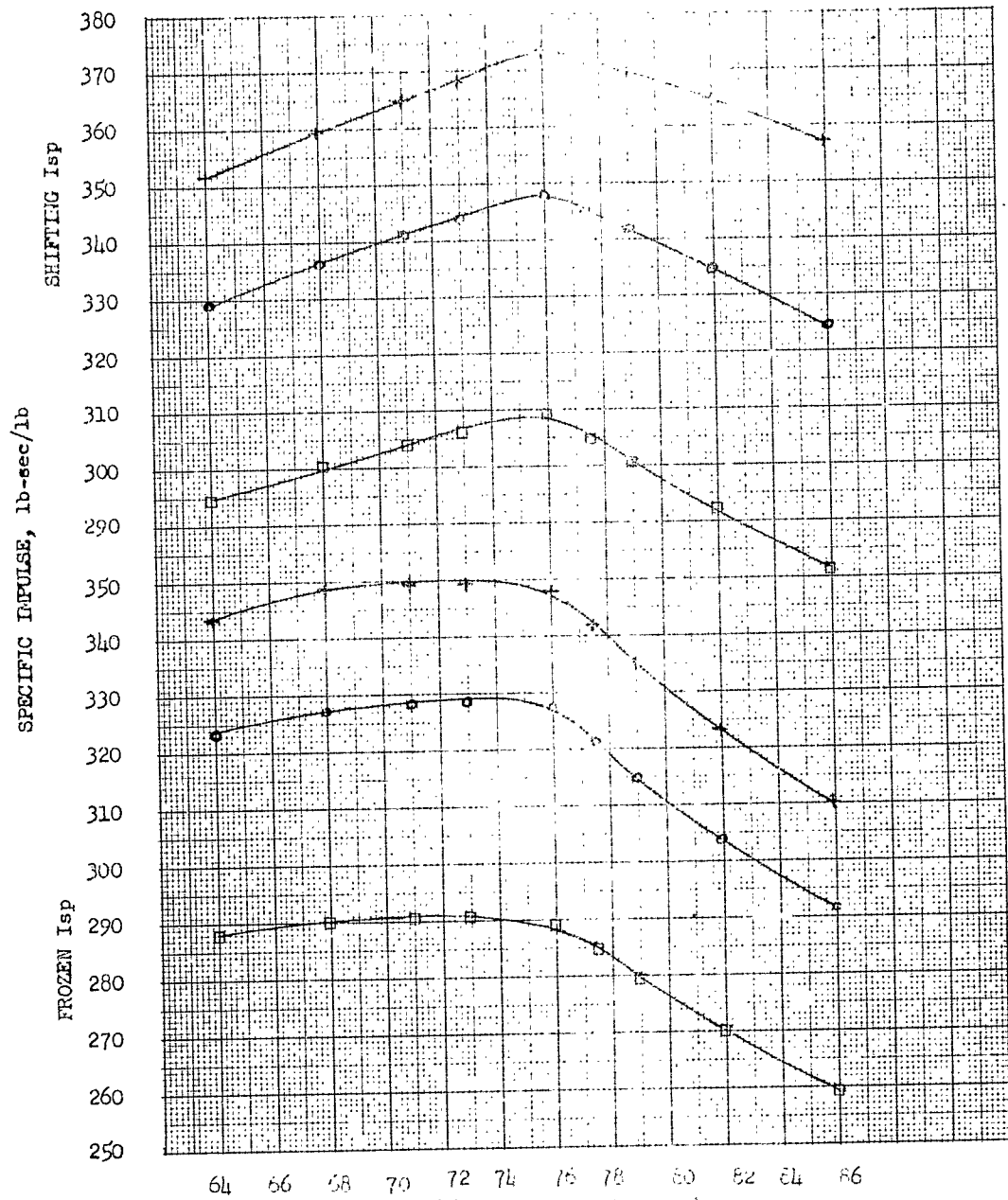
UDMH - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 74



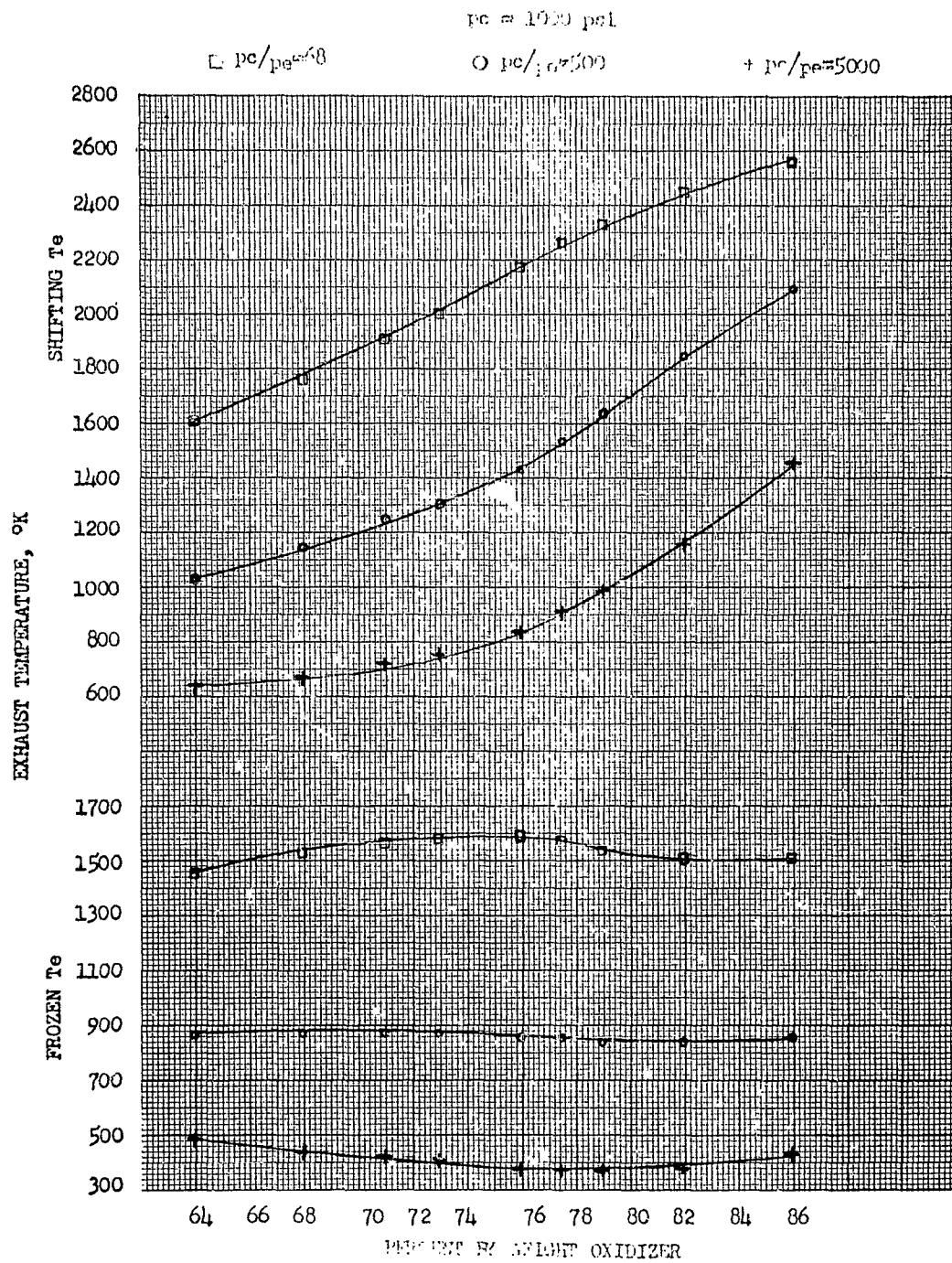


OPS/SEC

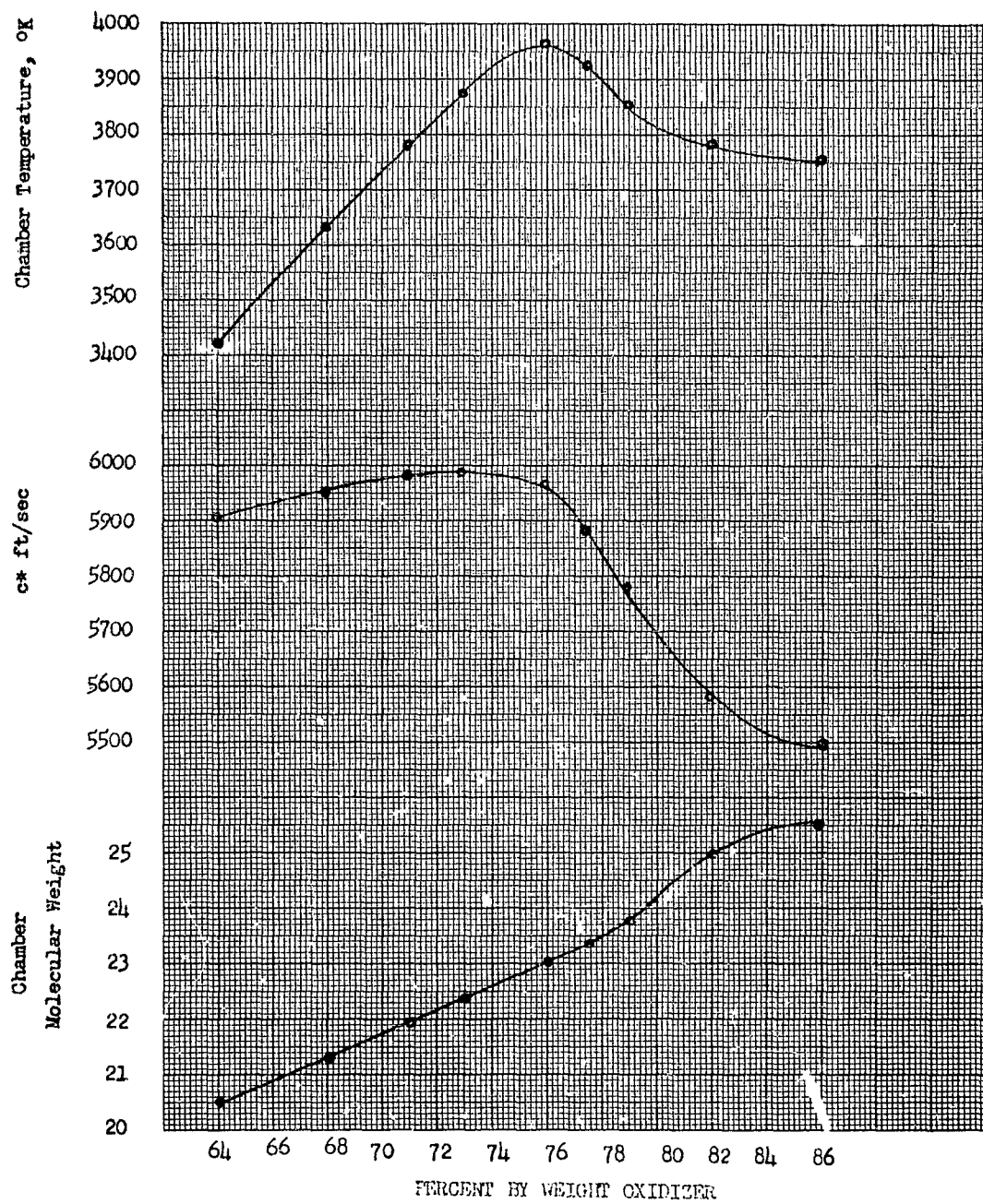
1000

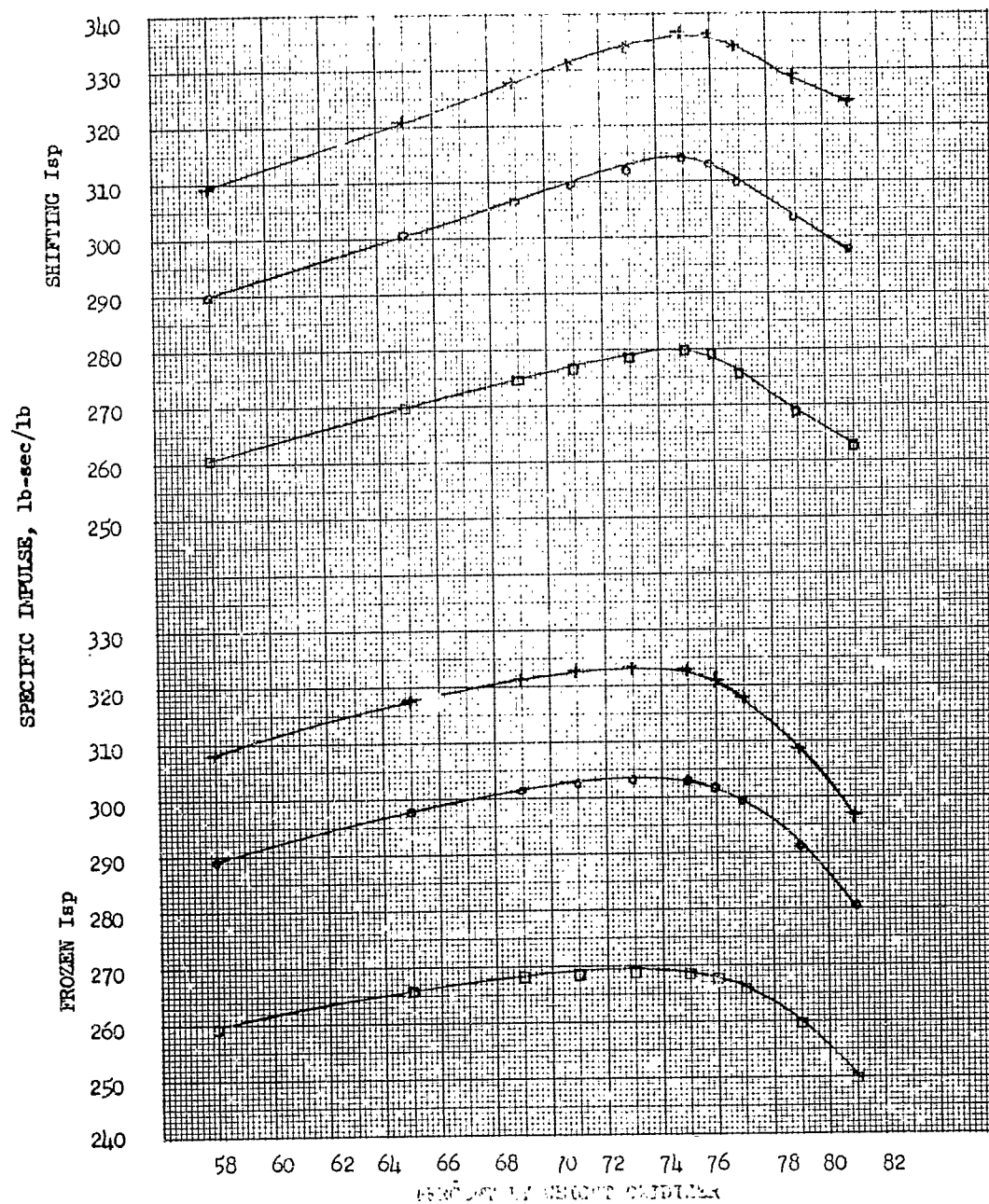


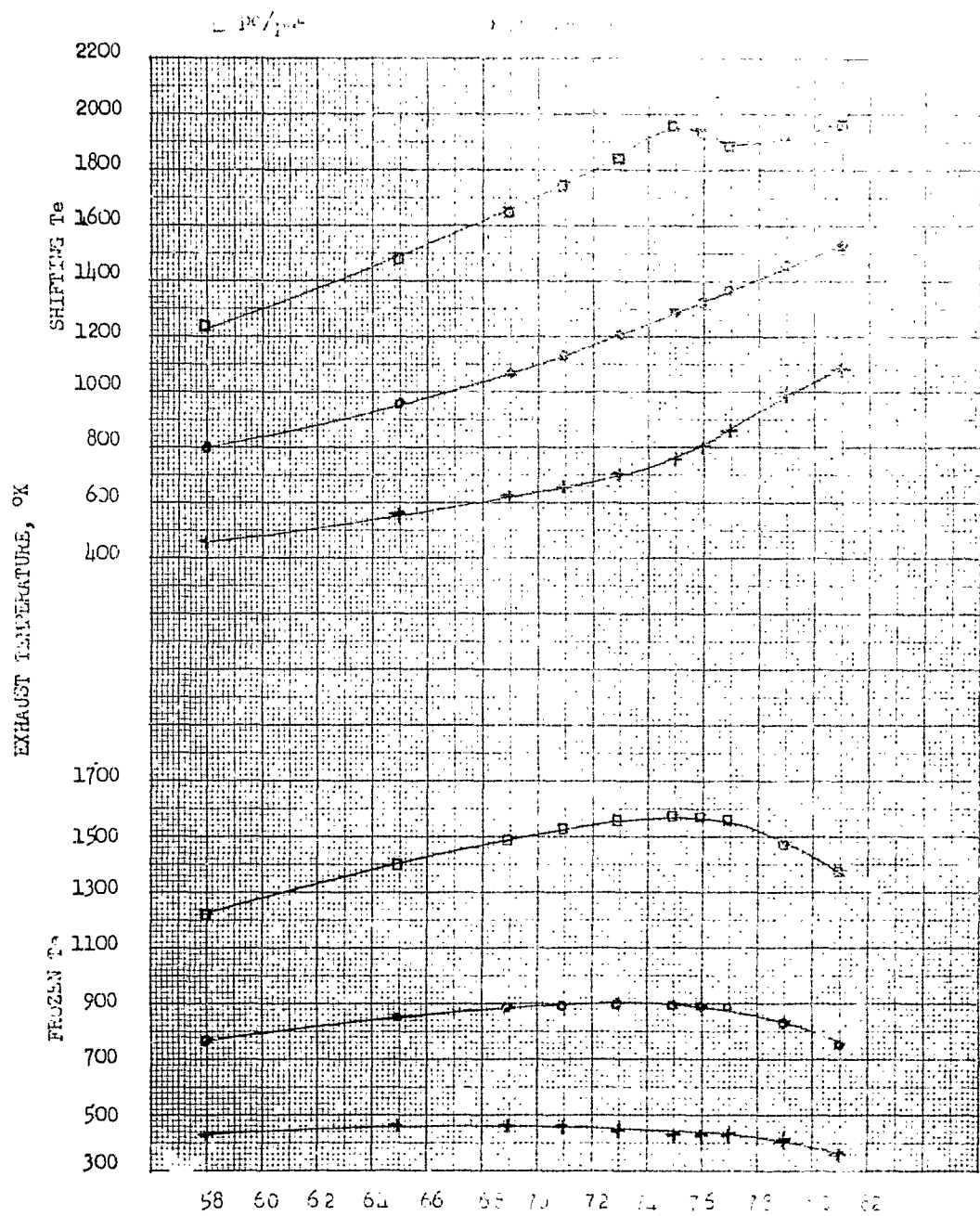
UDMH - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 77



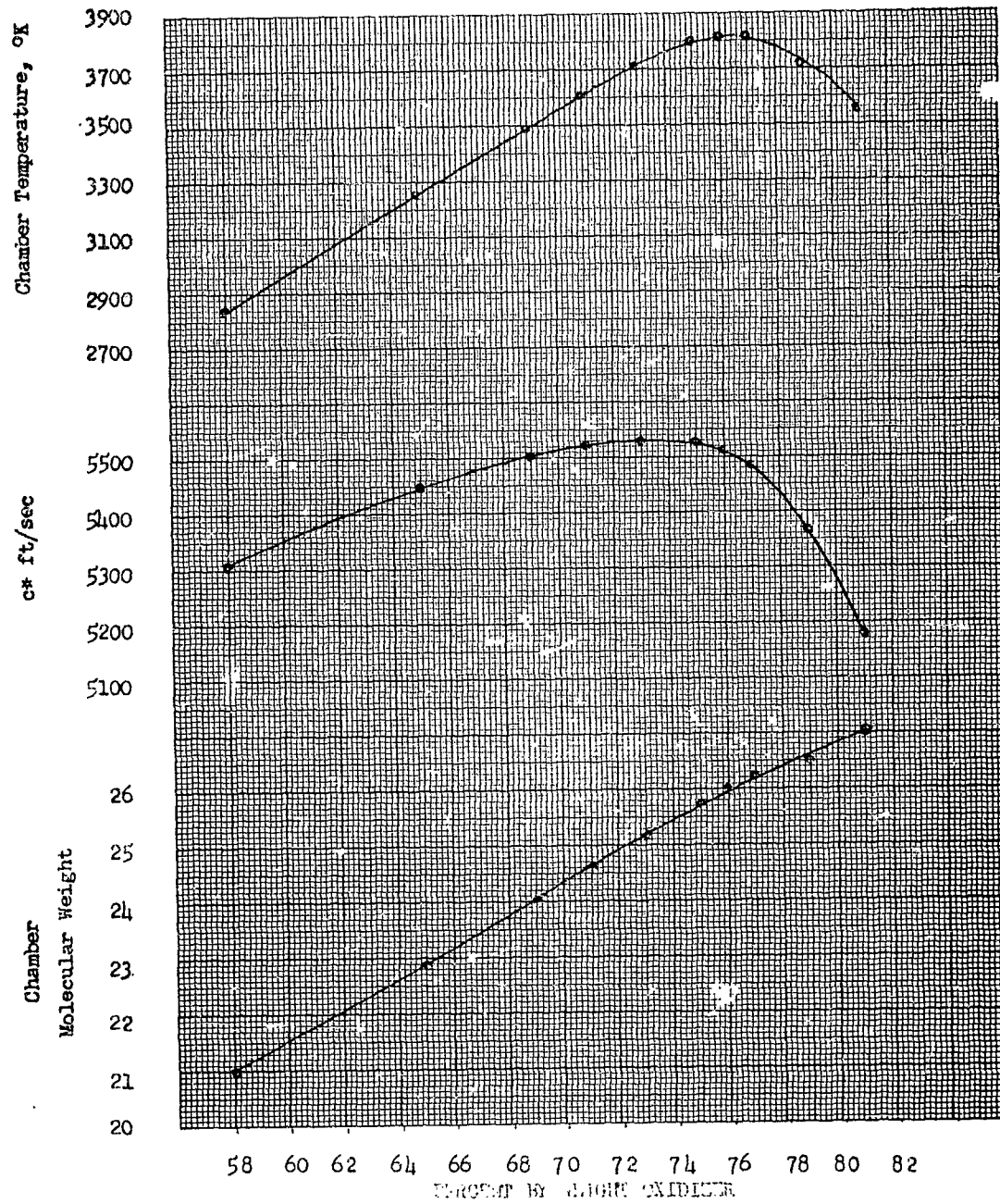
UDMH - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 78





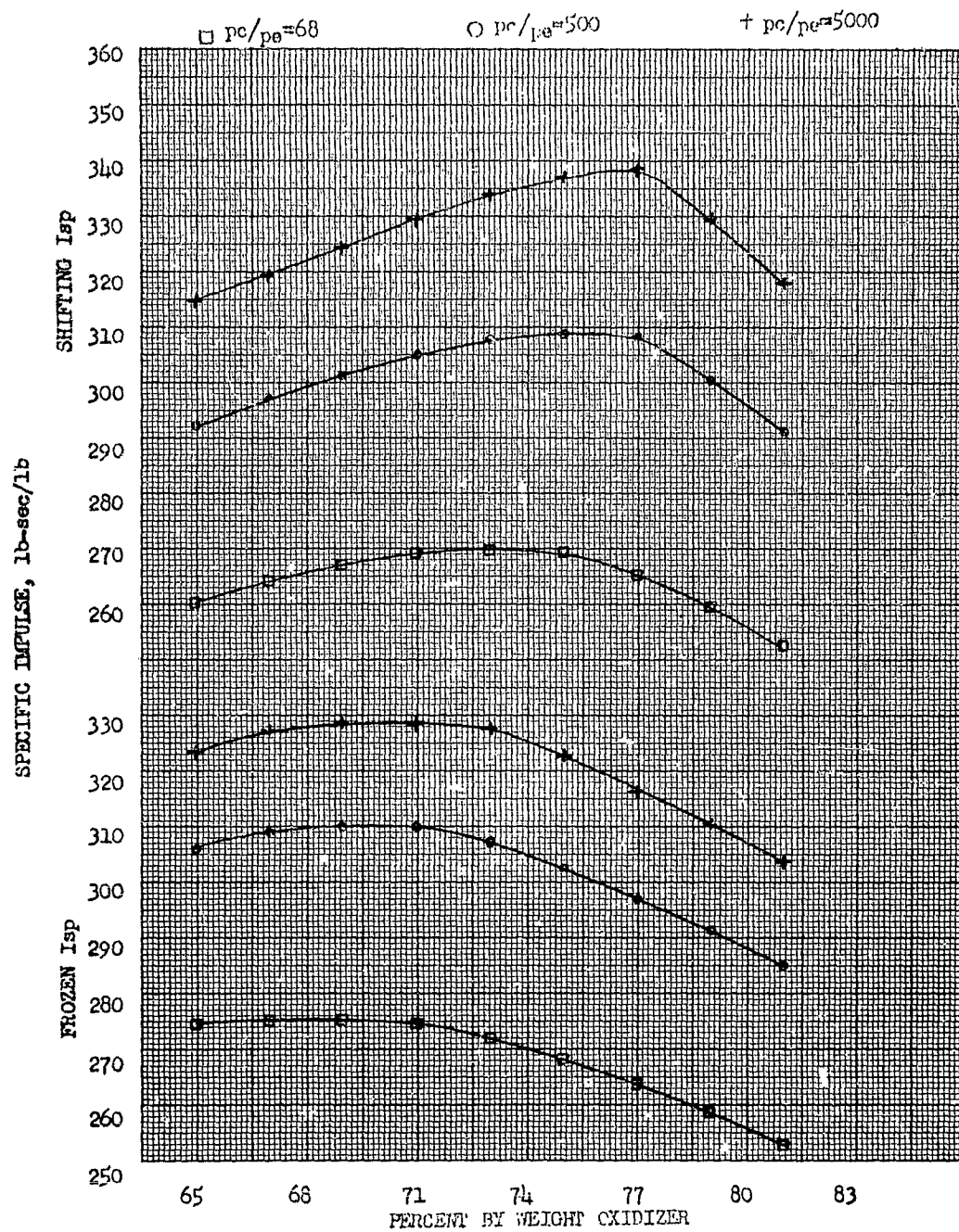


UDMH - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 81

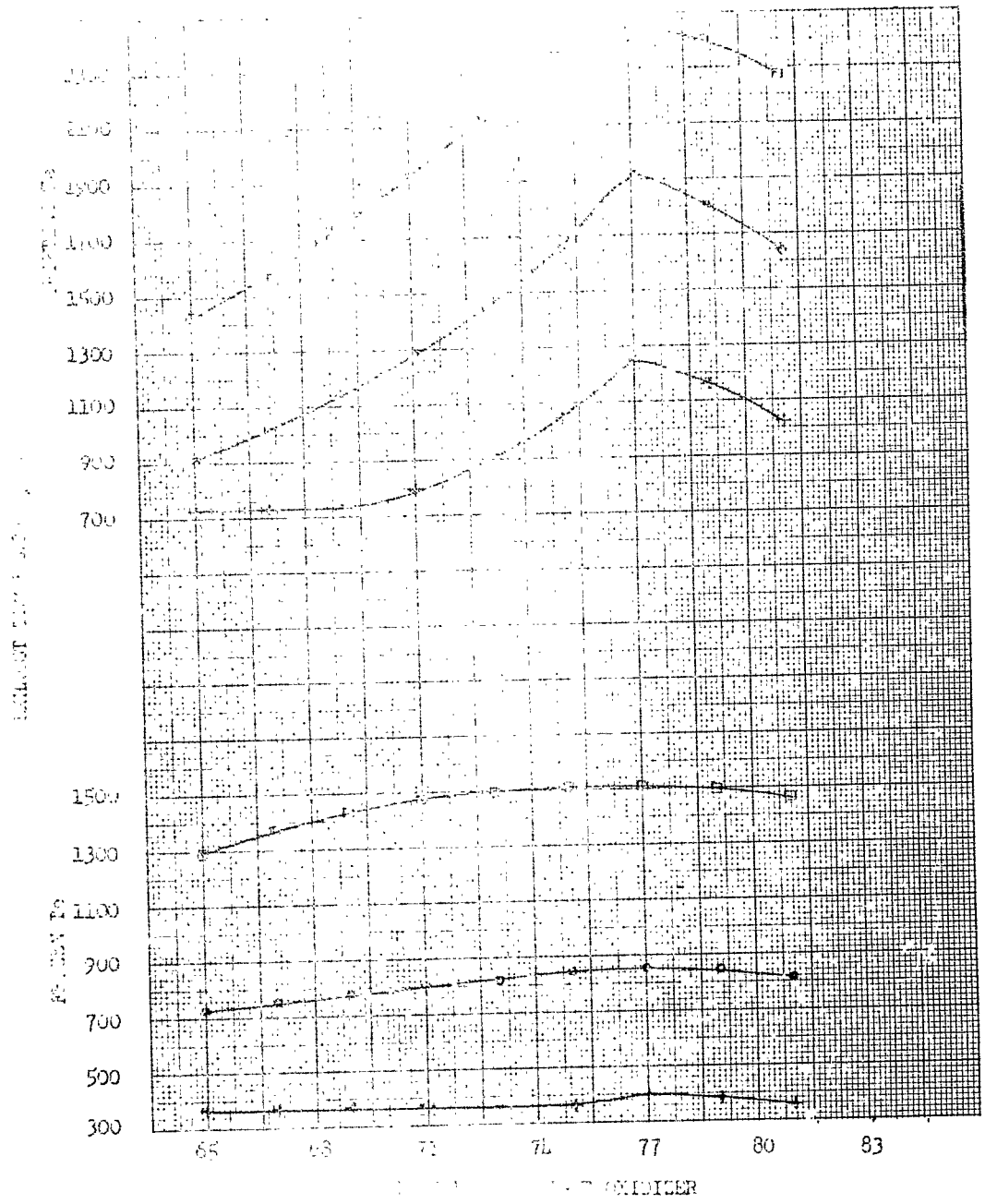


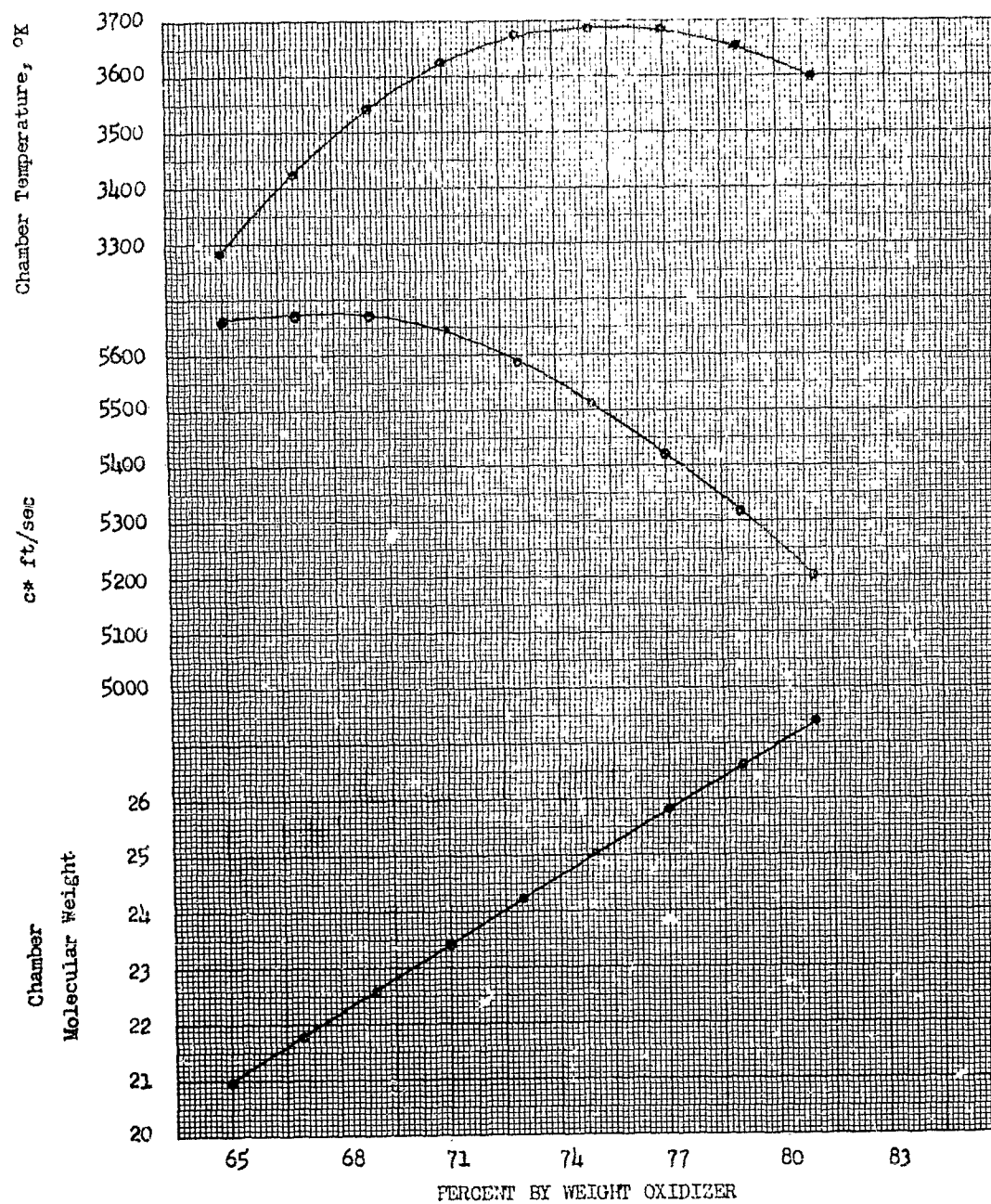
UDMH - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 82

$p_c = 1000 \text{ psi}$



100/5000





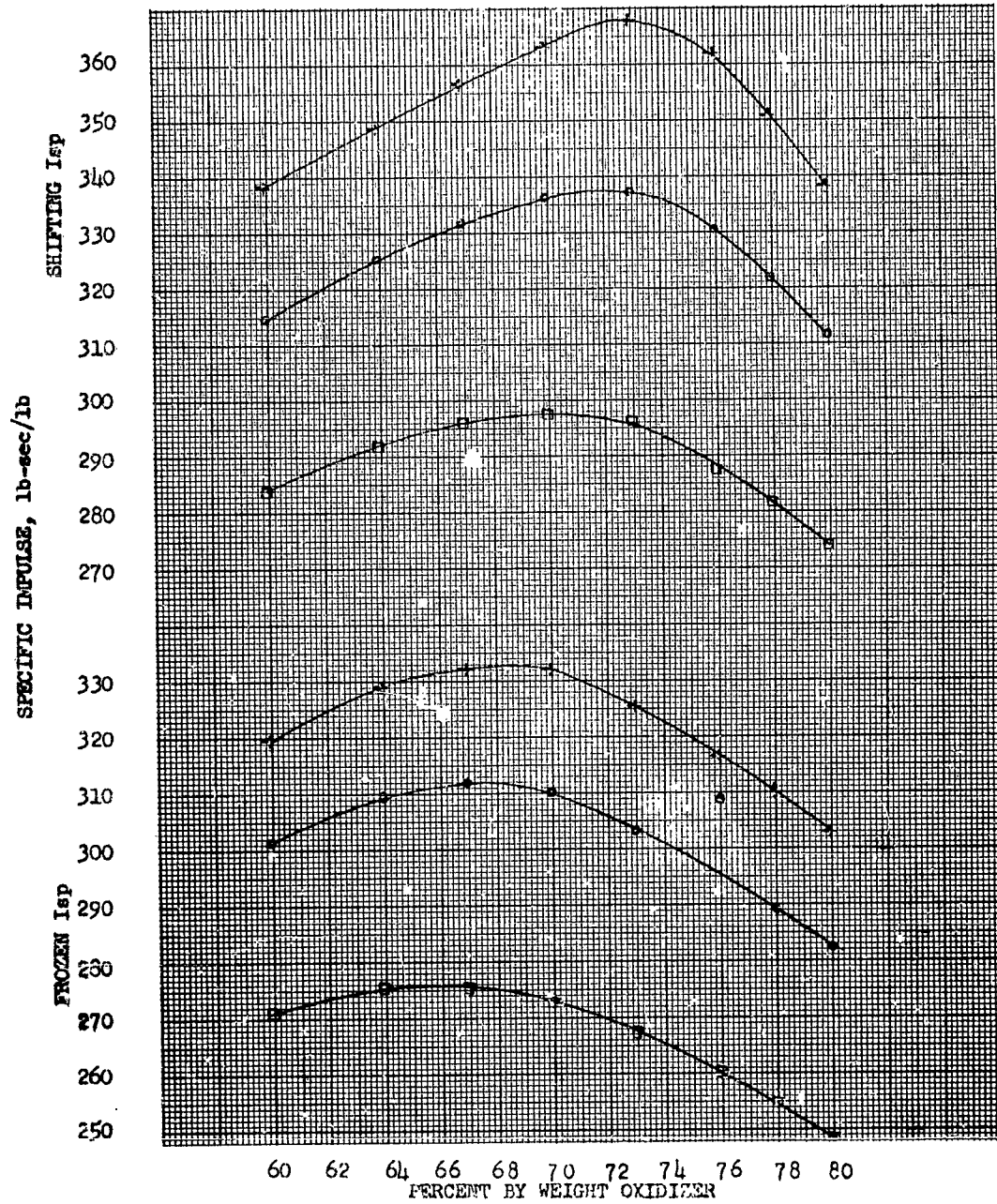
UDMH - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 85

$p_c = 1000 \text{ psi}$

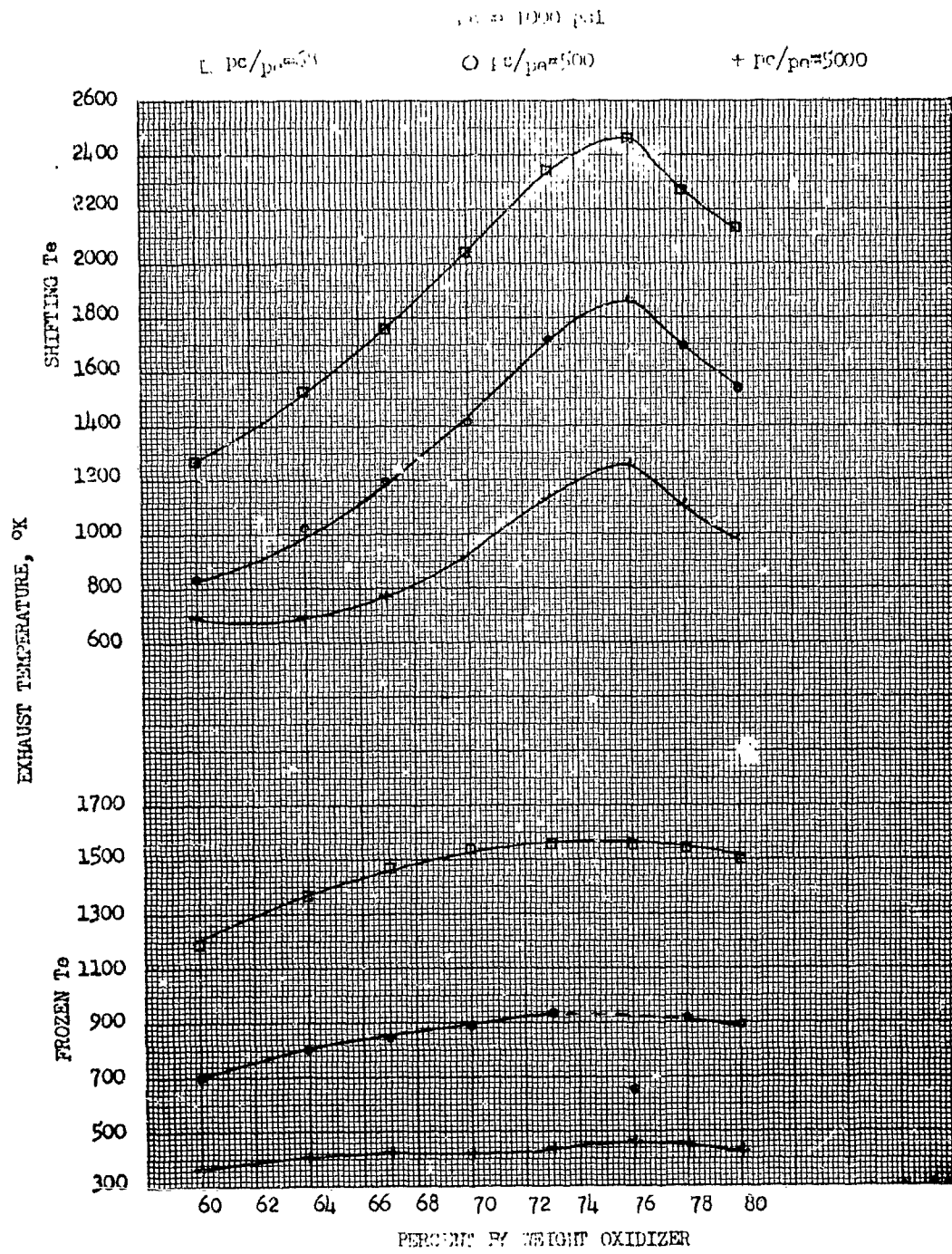
$\square p_c/p_e = 0.8$

$\circ p_c/p_e = 500$

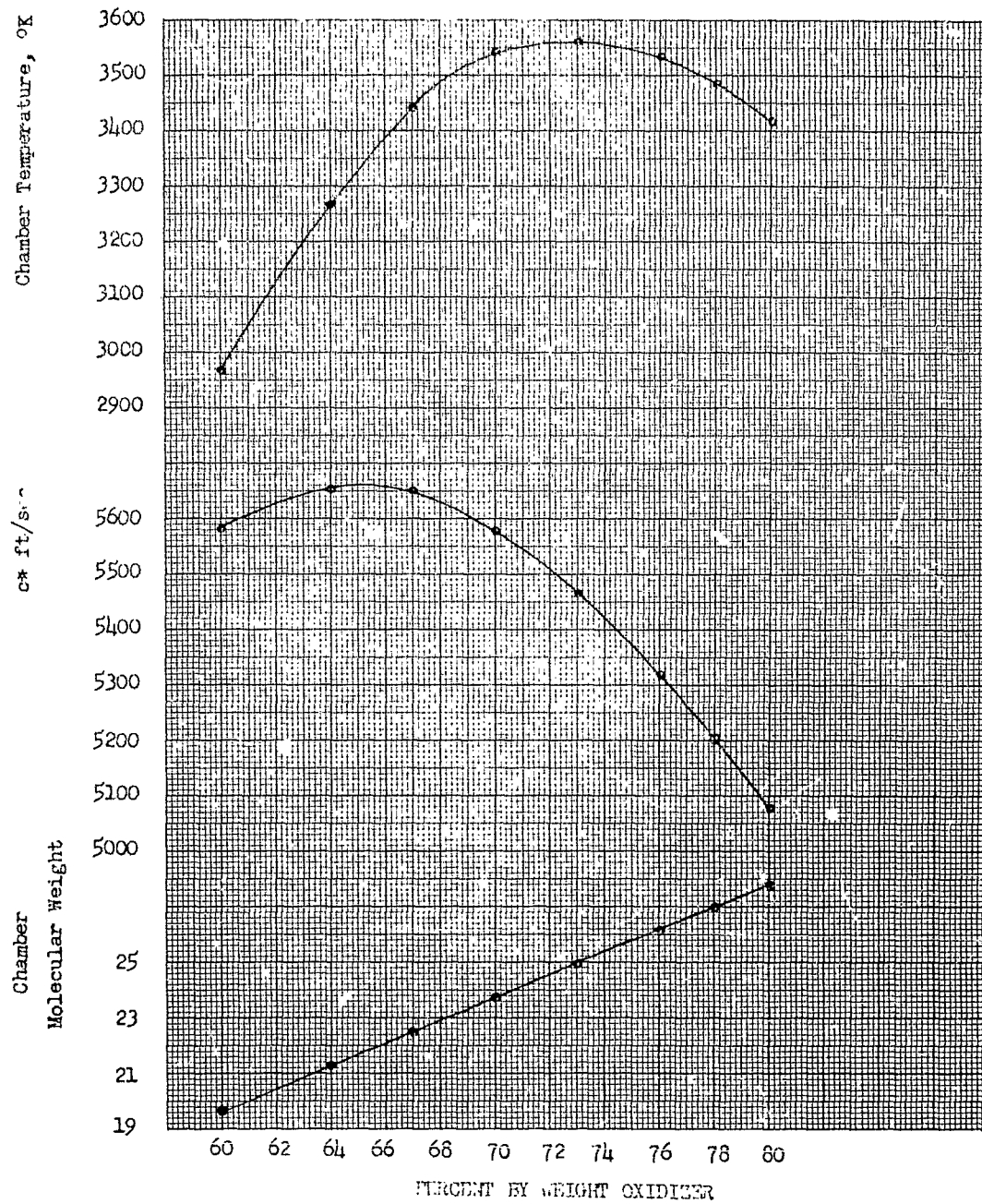
$+ p_c/p_e = 5000$

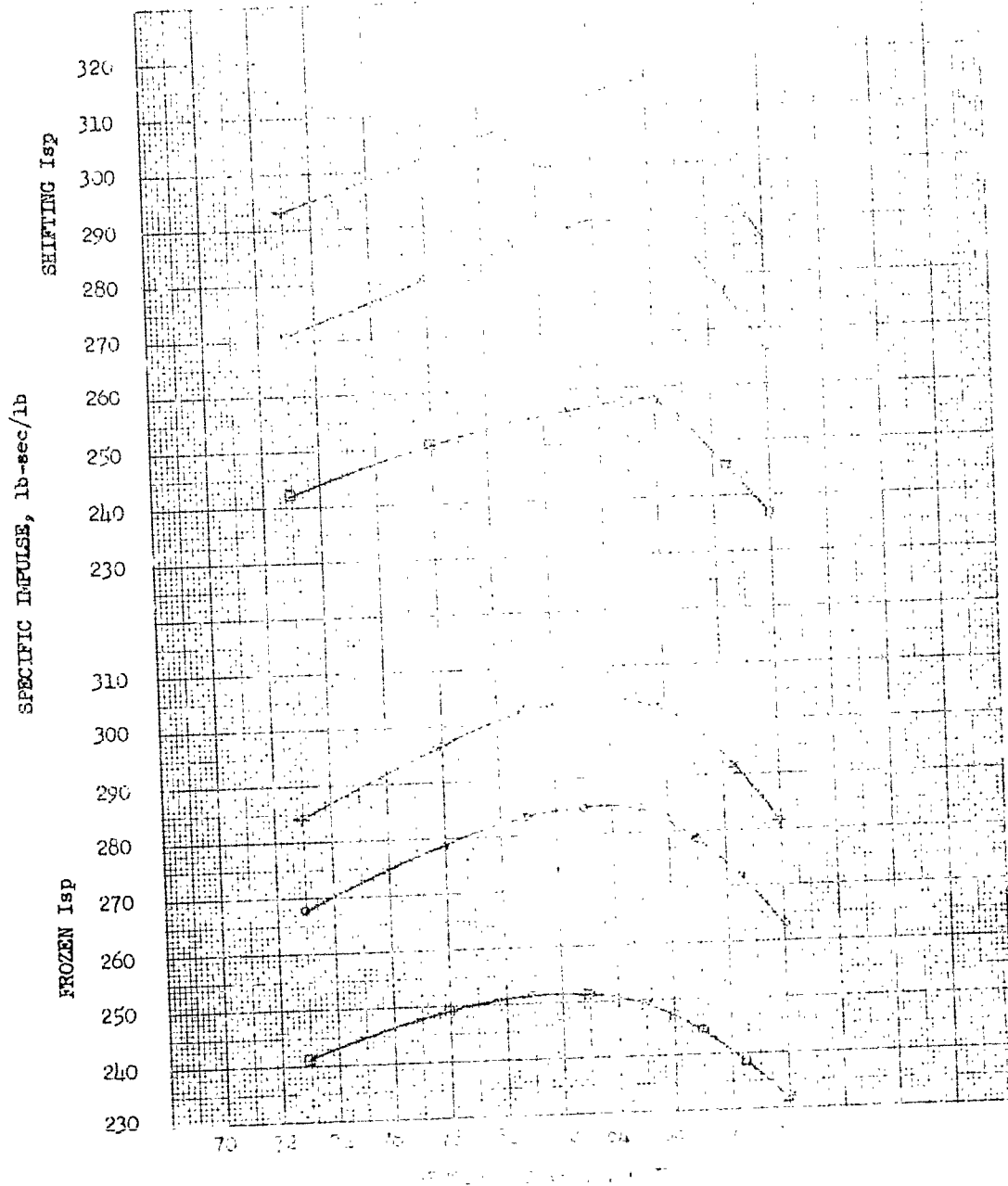


UDMH - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 86

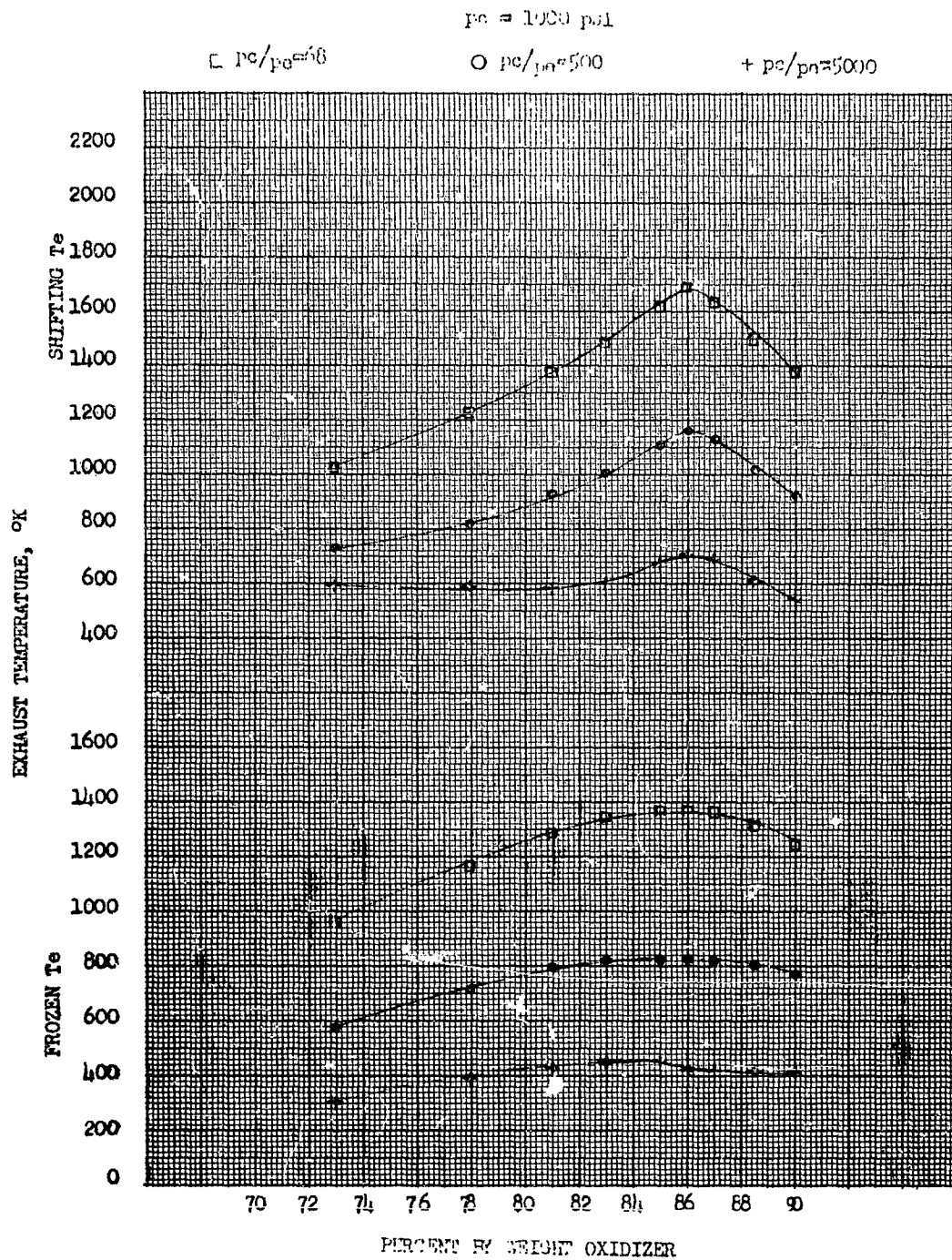


UDPH - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 87

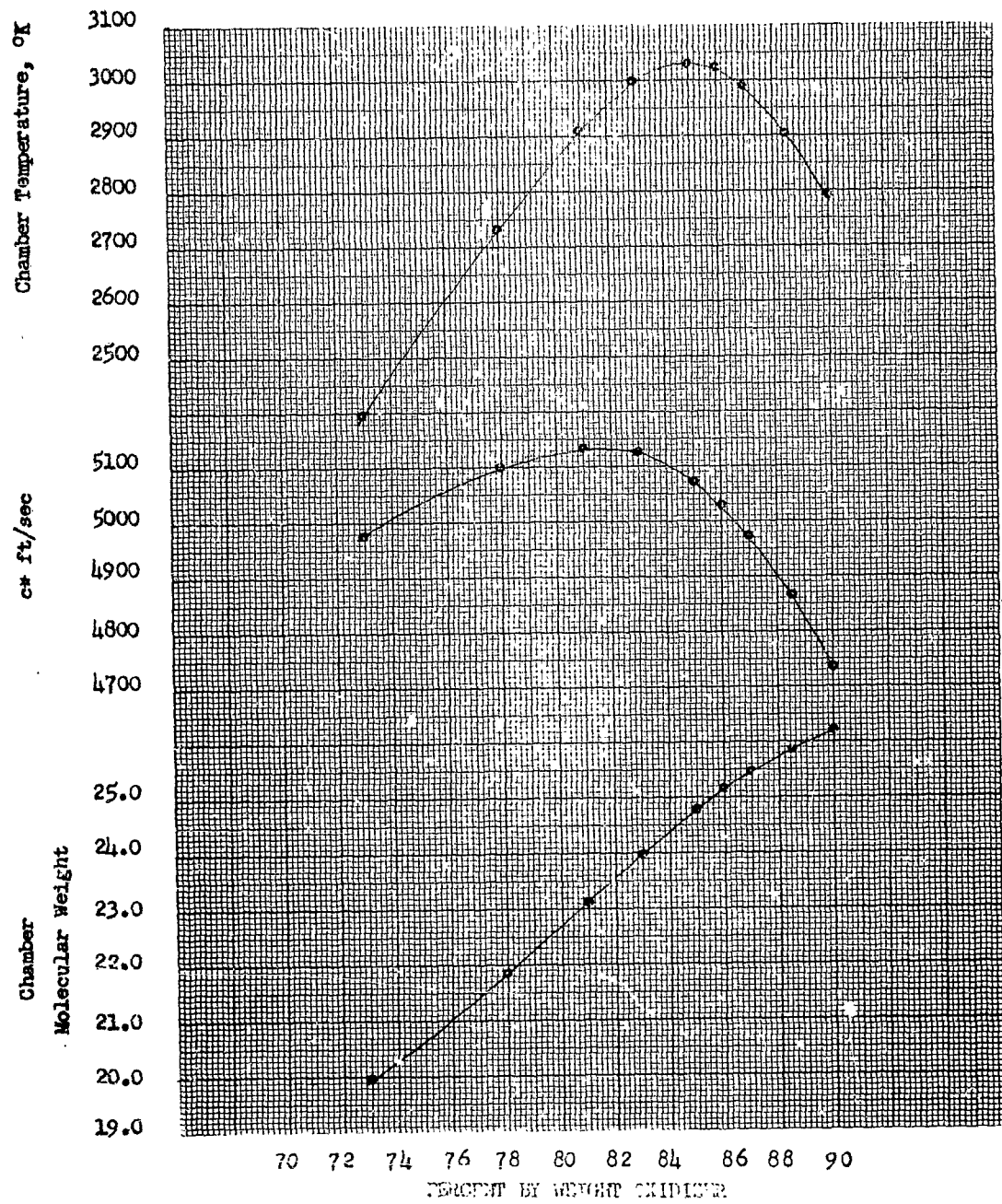




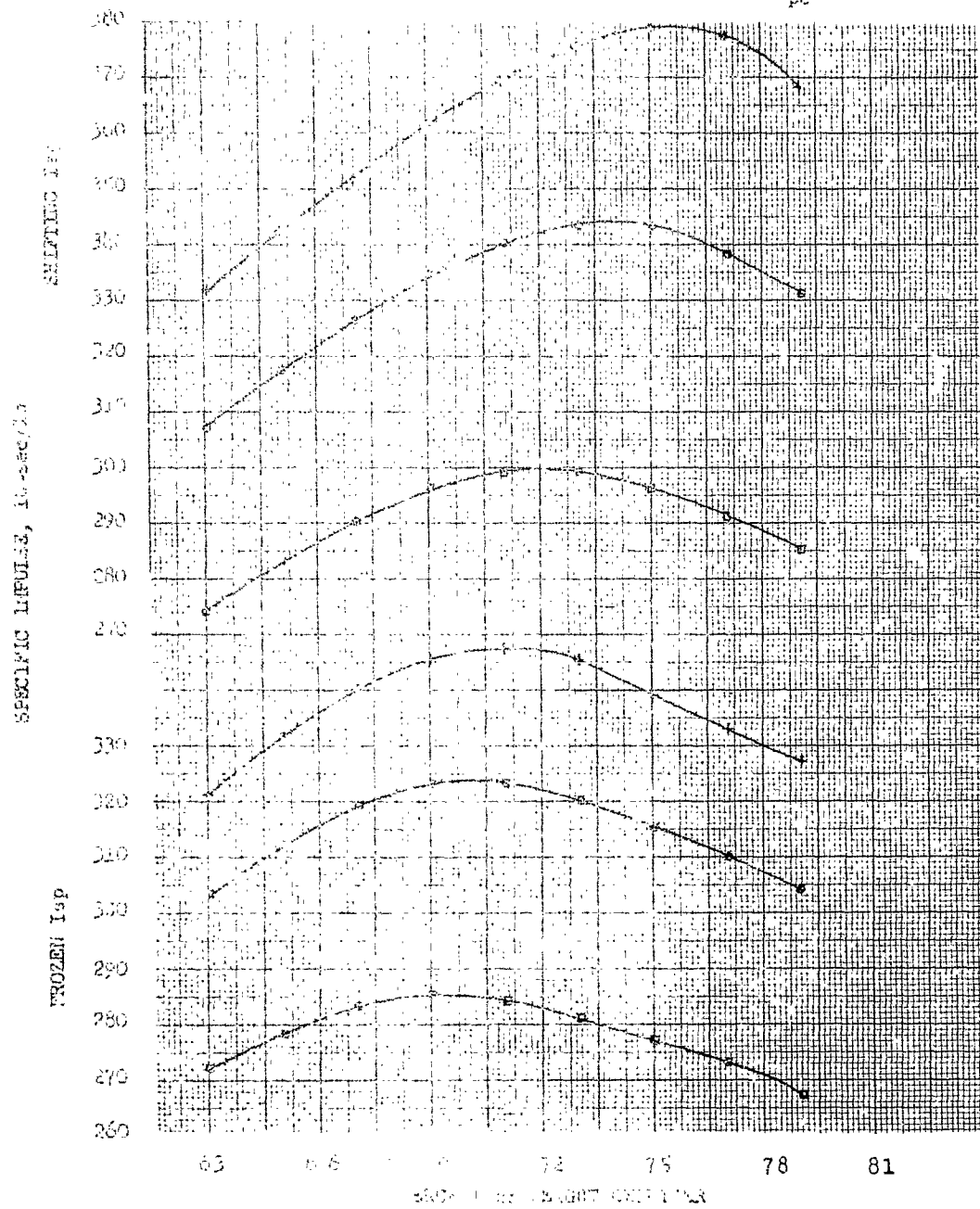
UDHM - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 89



UDMH - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 90



+ $\mu_c/\mu_e = 5000$

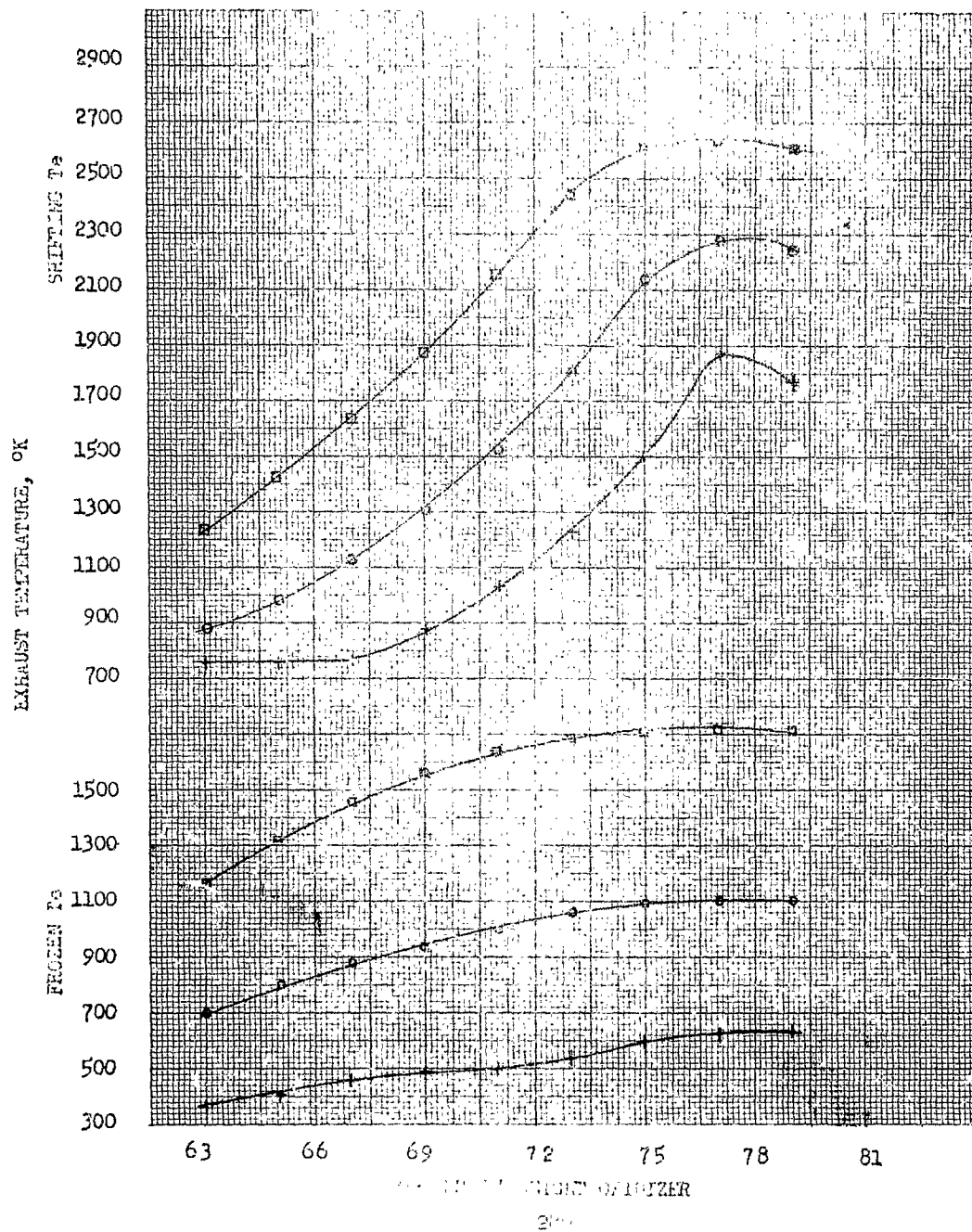


POLYETHYLENE - 100% CRYSTALLINE

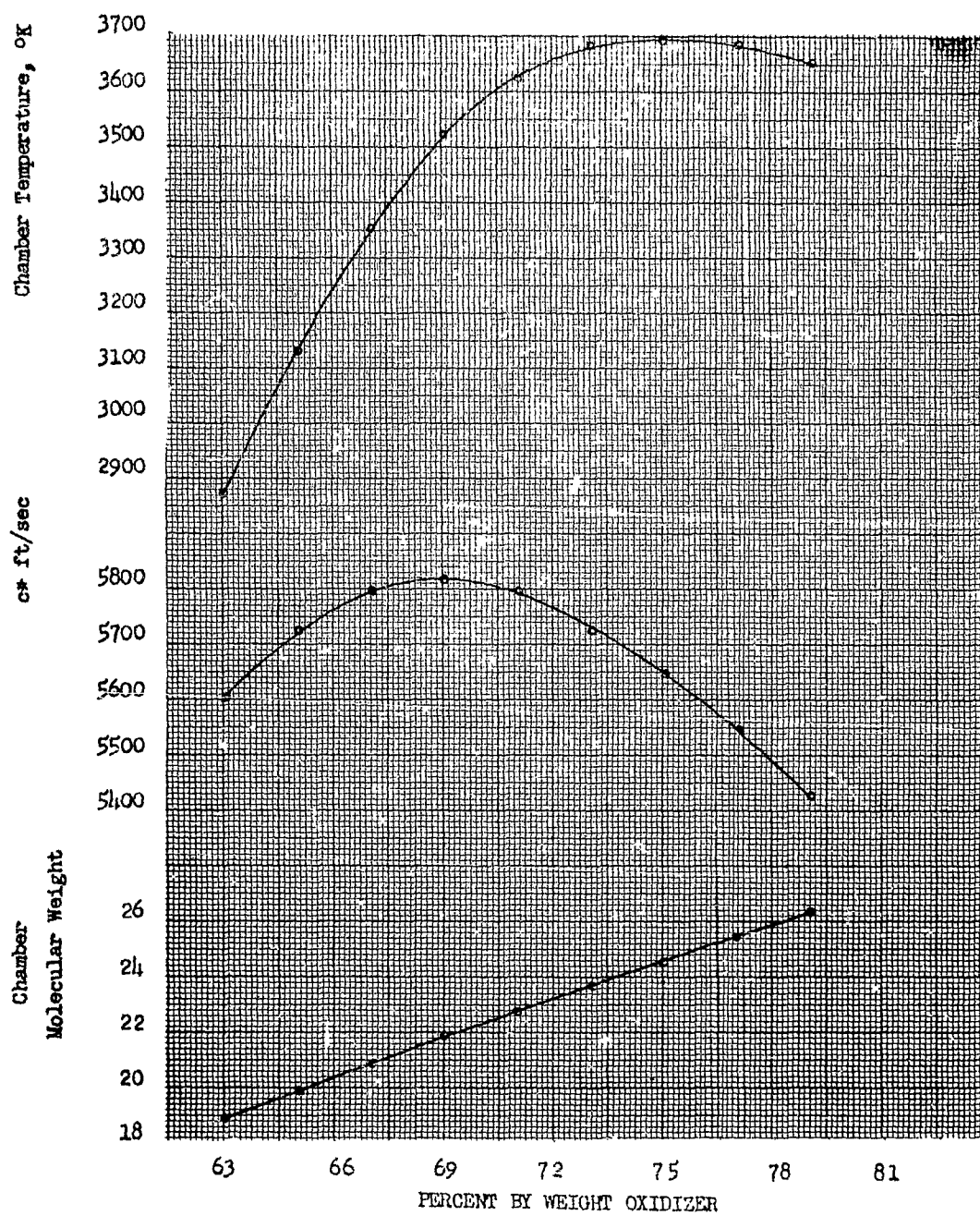
100/1000

100/1000

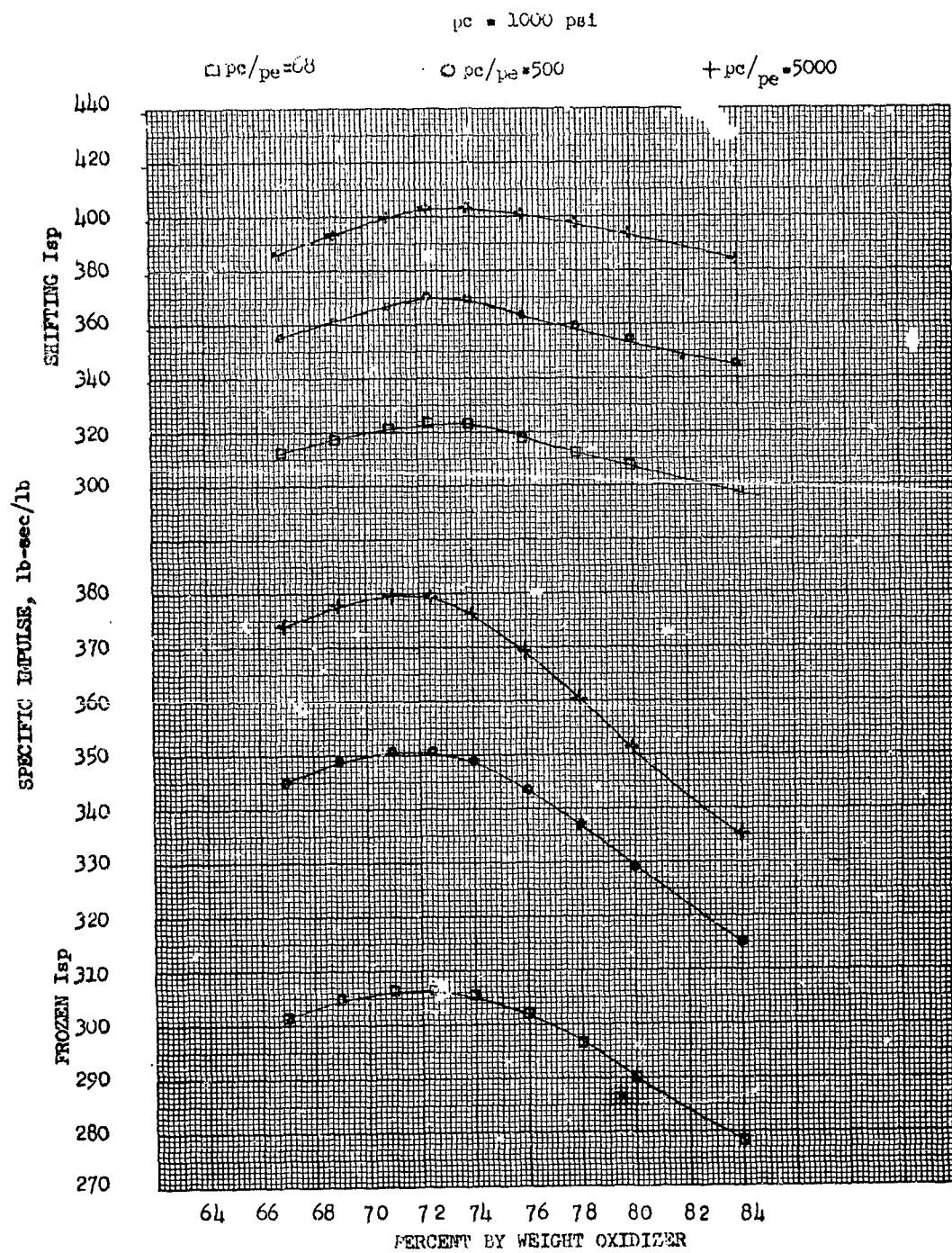
100/1000

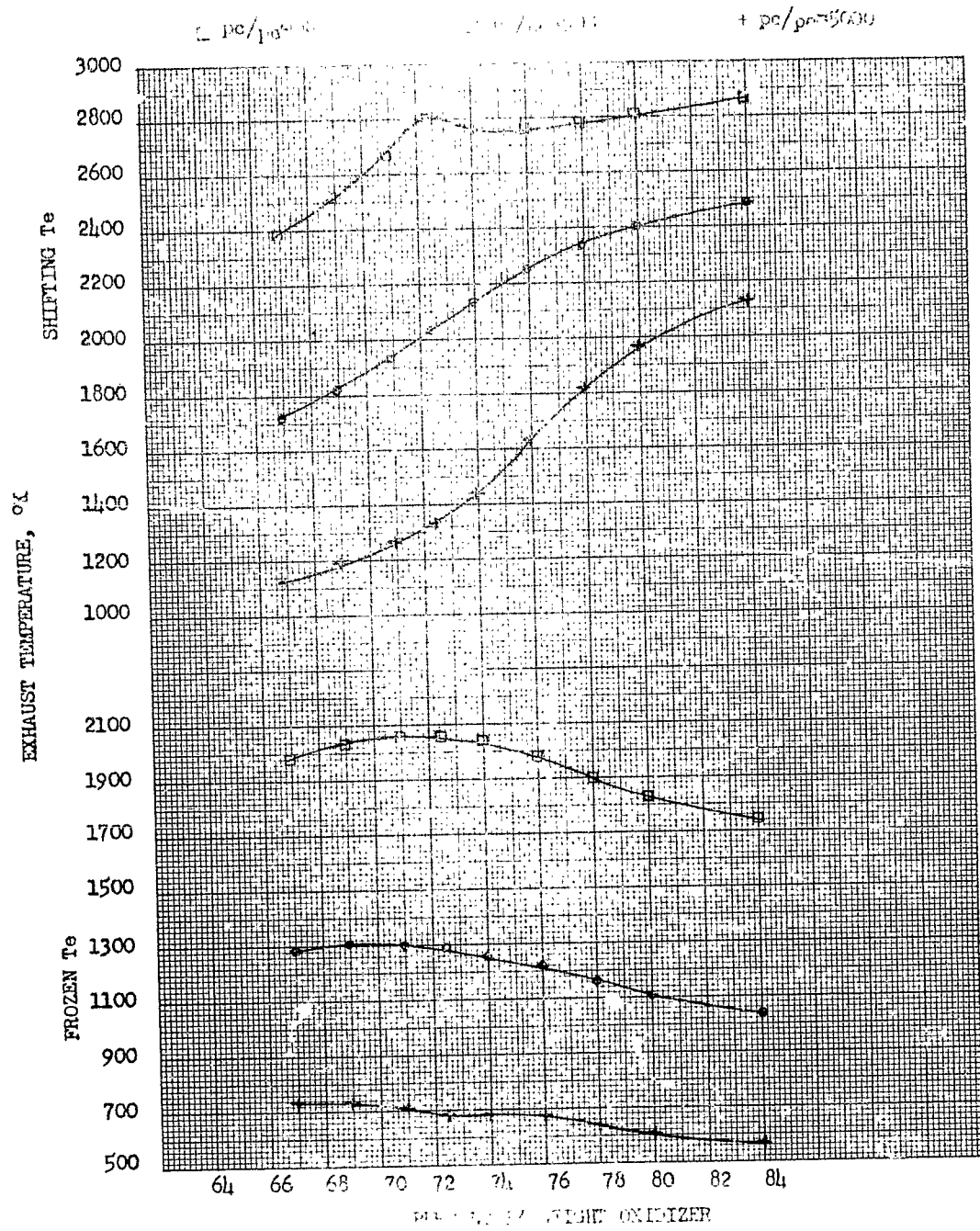


POLYETHYLENE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 93

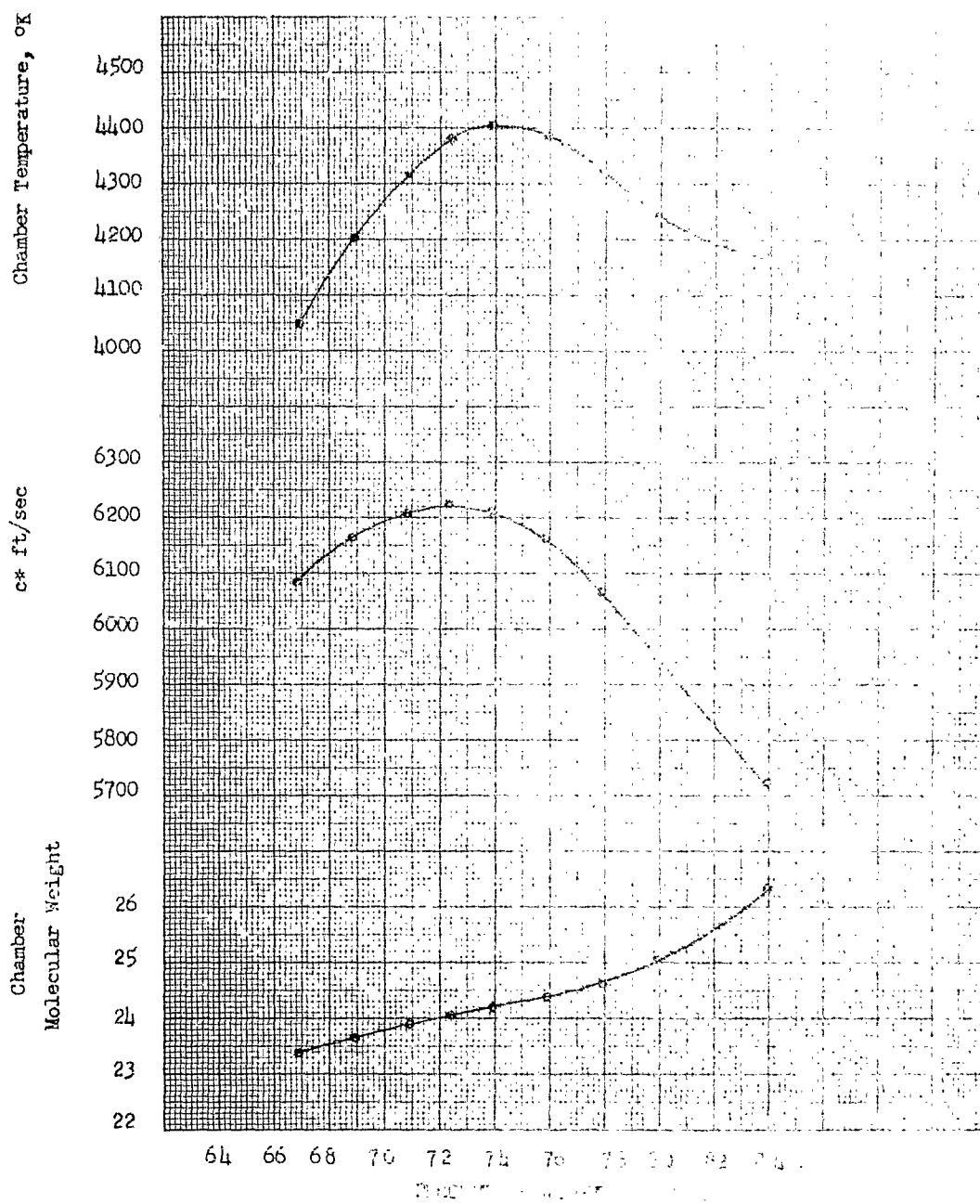


POLYETHYLENE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 94





POLYETHYLENE - LIQUID FLOW



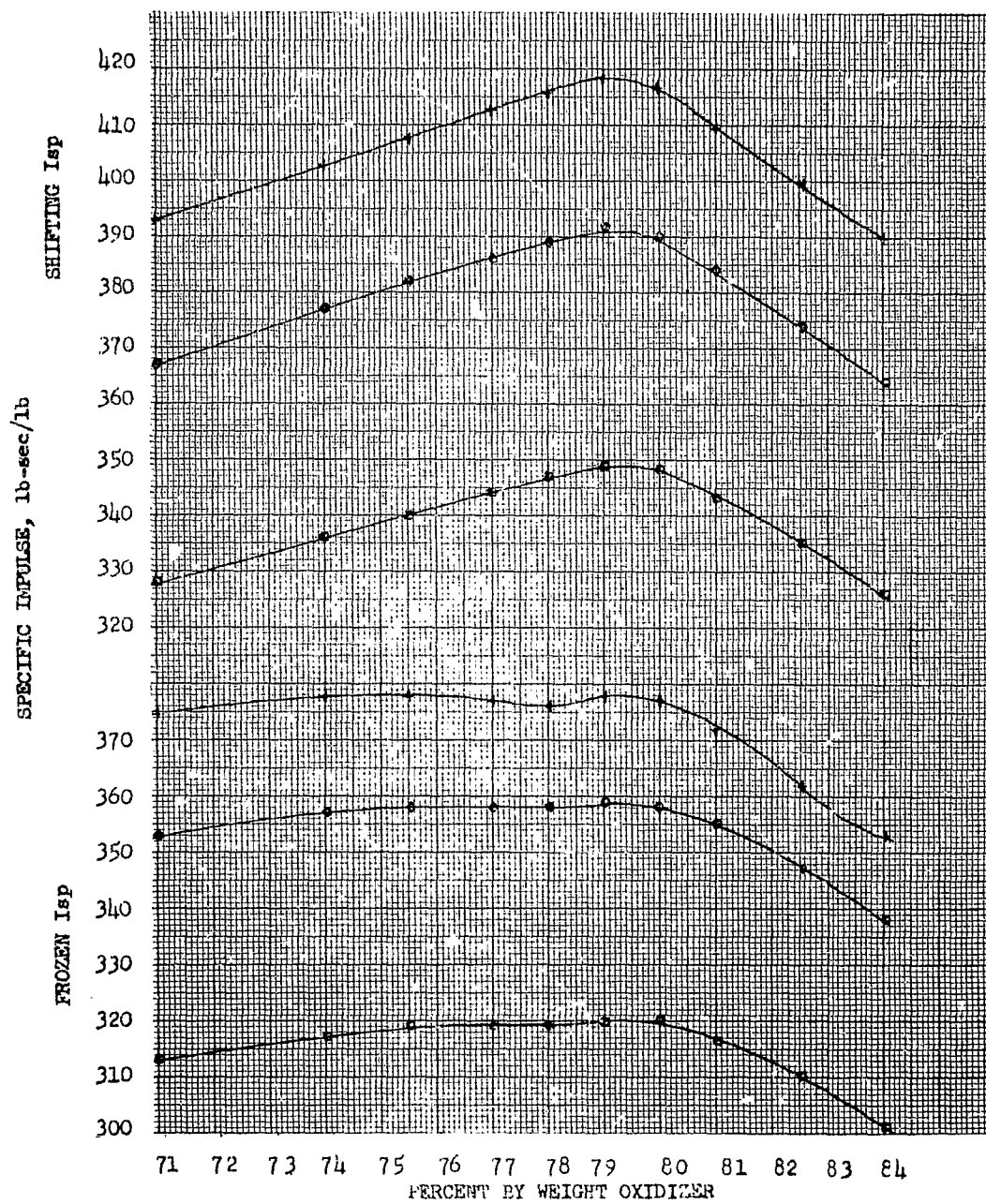
POLYETHYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 97

$p_c = 1000 \text{ psi}$

$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$



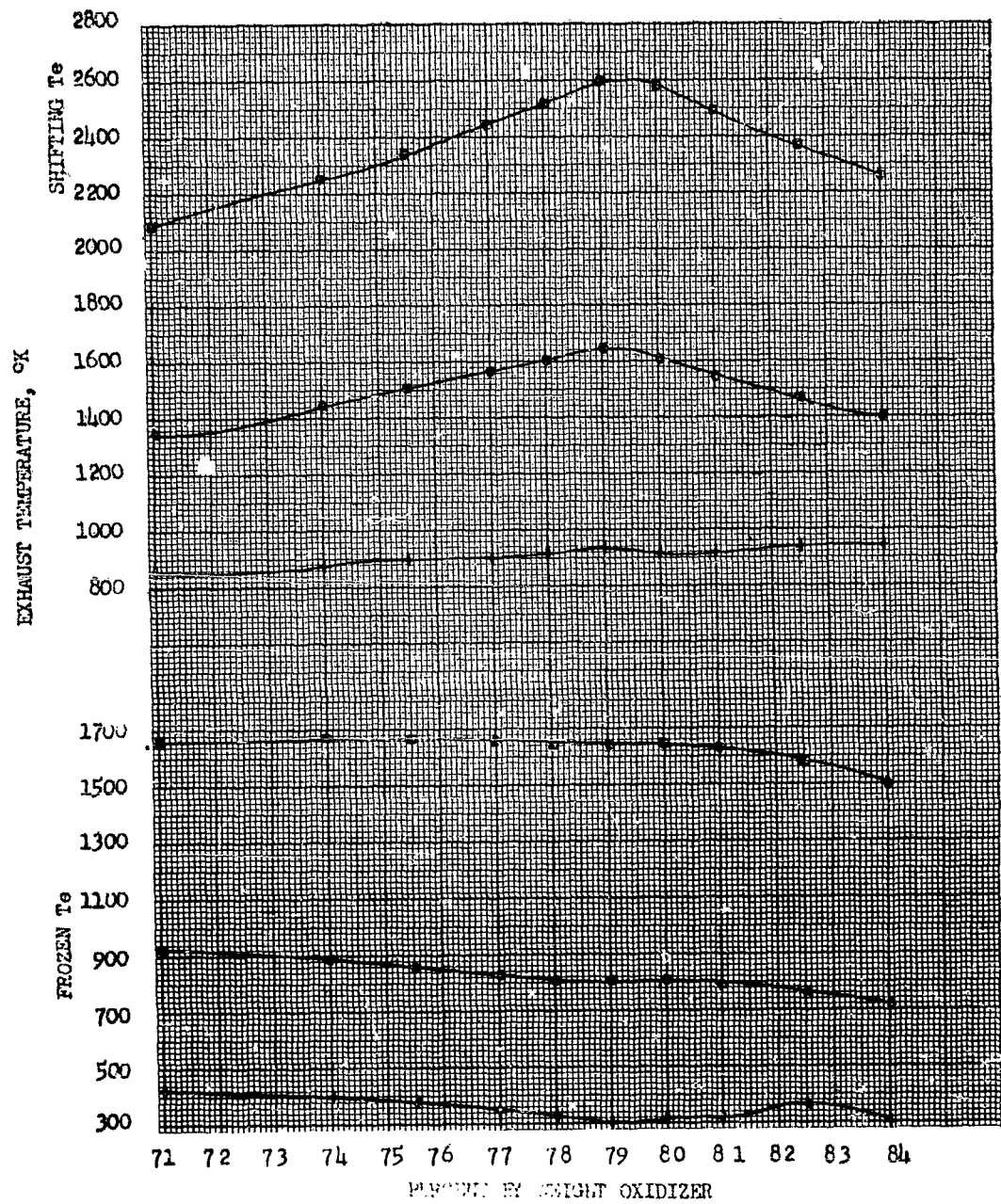
POLYETHYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 98

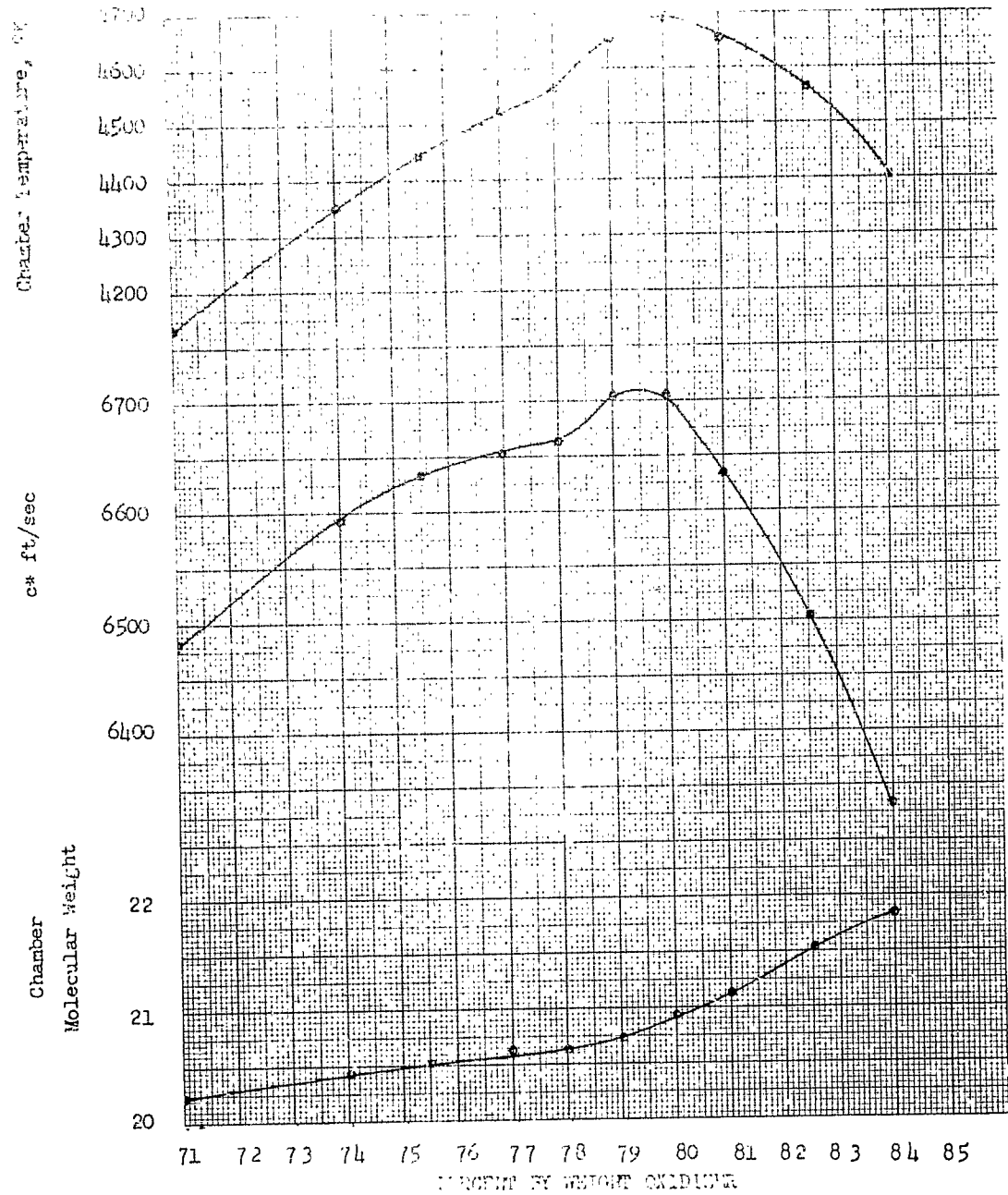
pc = 1000 psi

□ pc/p_o=68

○ pc/p_o=500

+ pc/p_o=5000





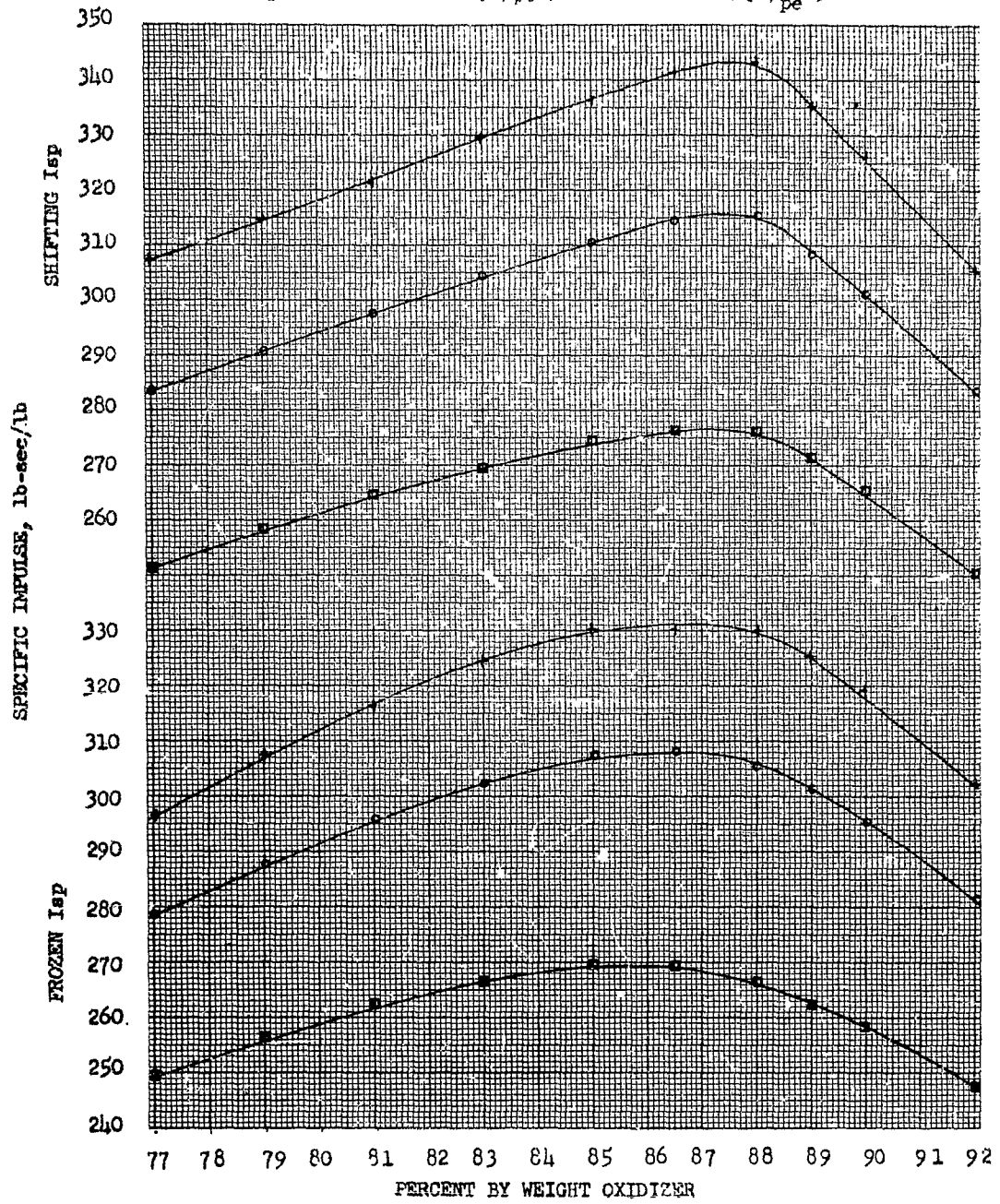
POLYETHYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 100

$p_c = 1000 \text{ psi}$

$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$



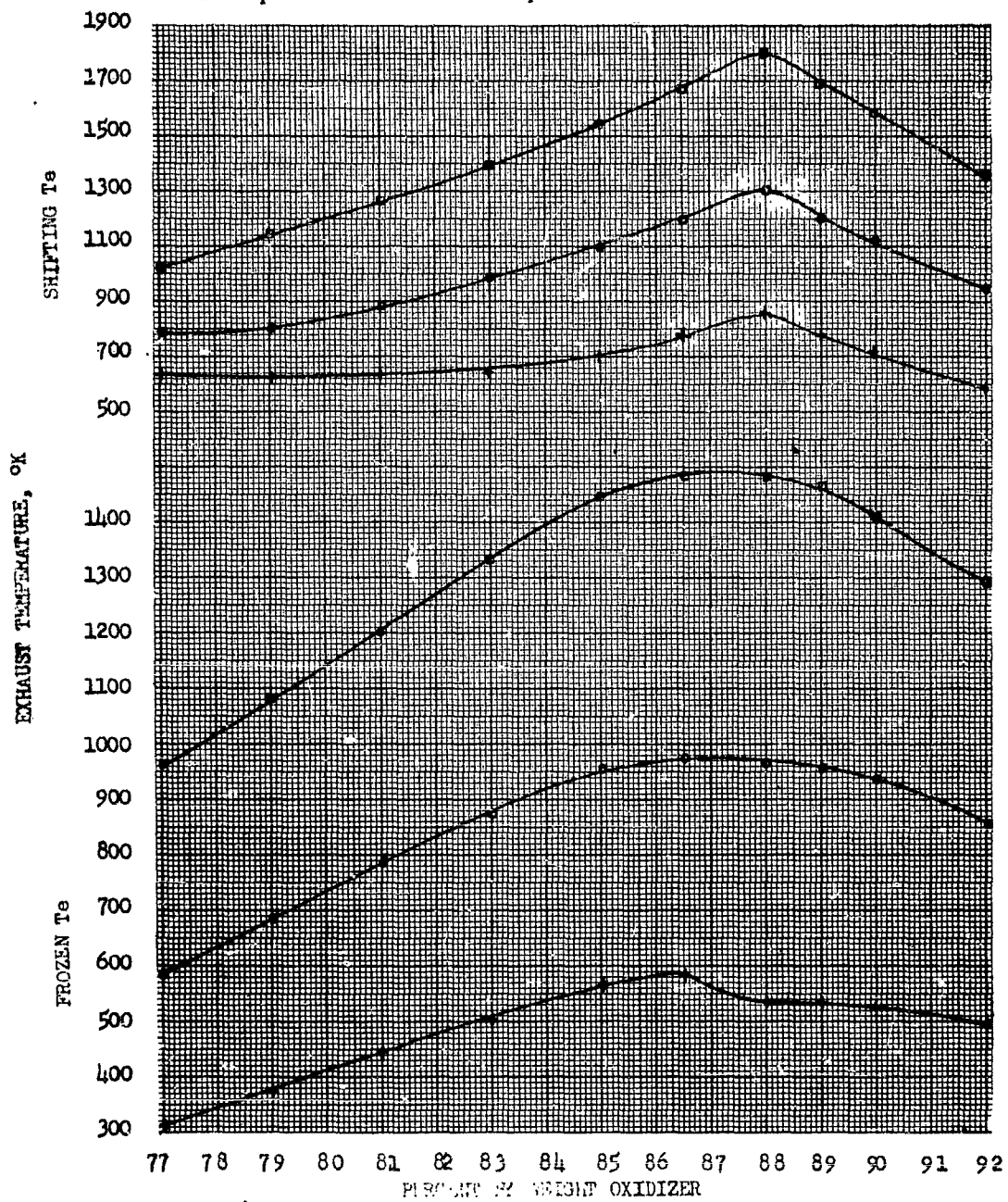
POLYETHYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 101

pc = 1000 psi

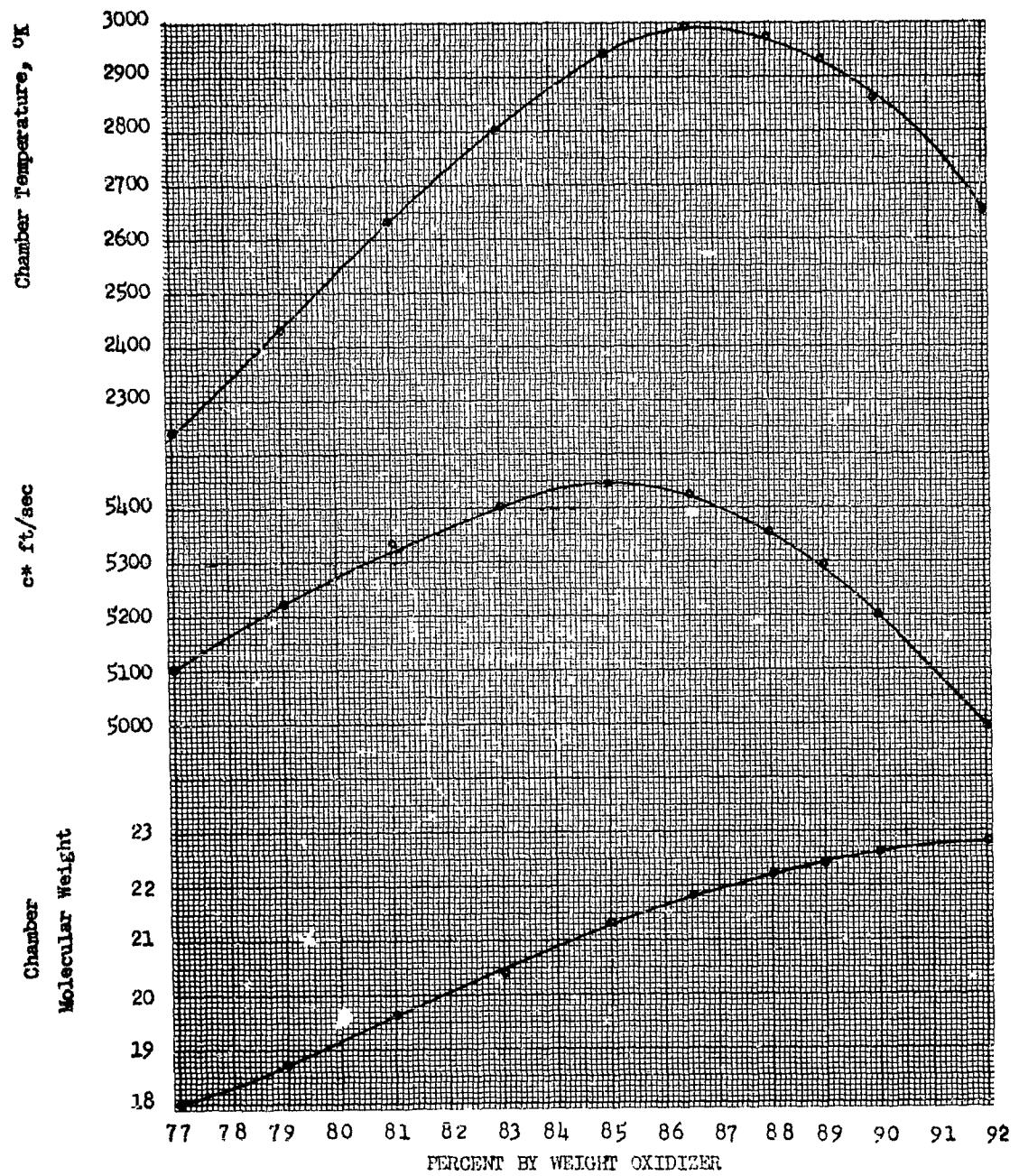
□ pc/p_e=68

○ pc/p_e=500

+ pc/p_e=5000



POLYETHYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 102



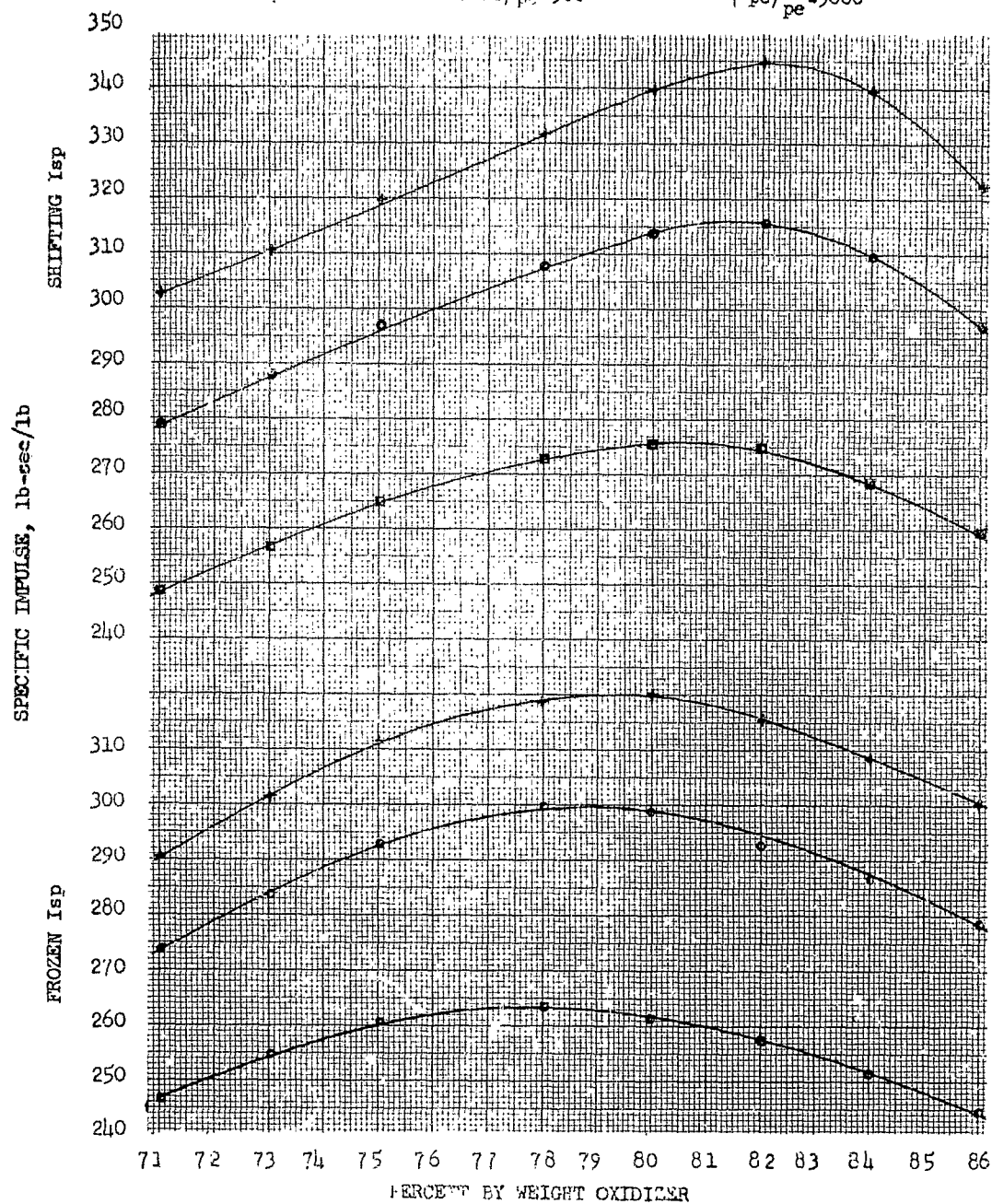
POLYETHYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 103

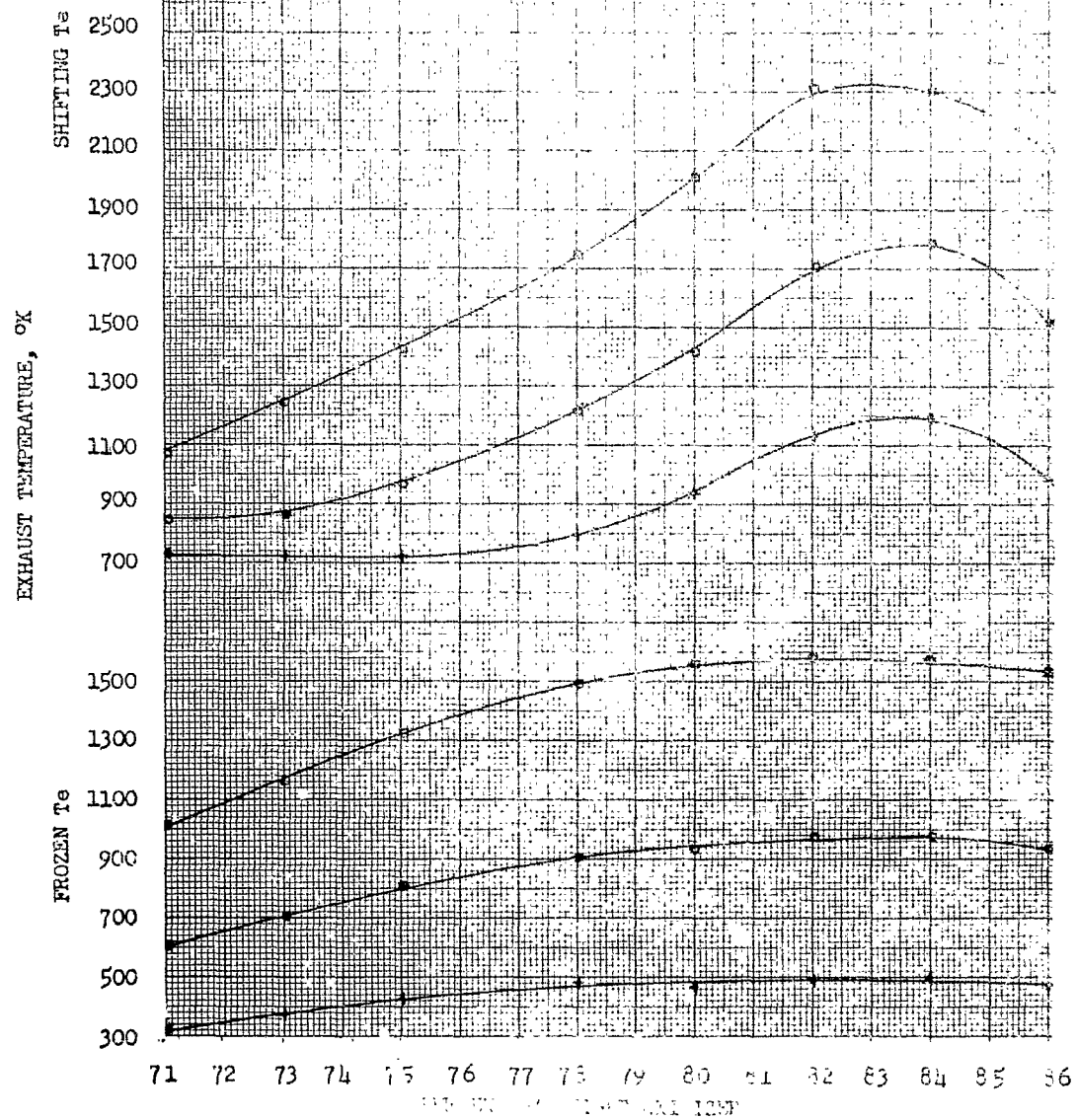
$p_c = 1000 \text{ psi}$

$\square p_c/p_e = 200$

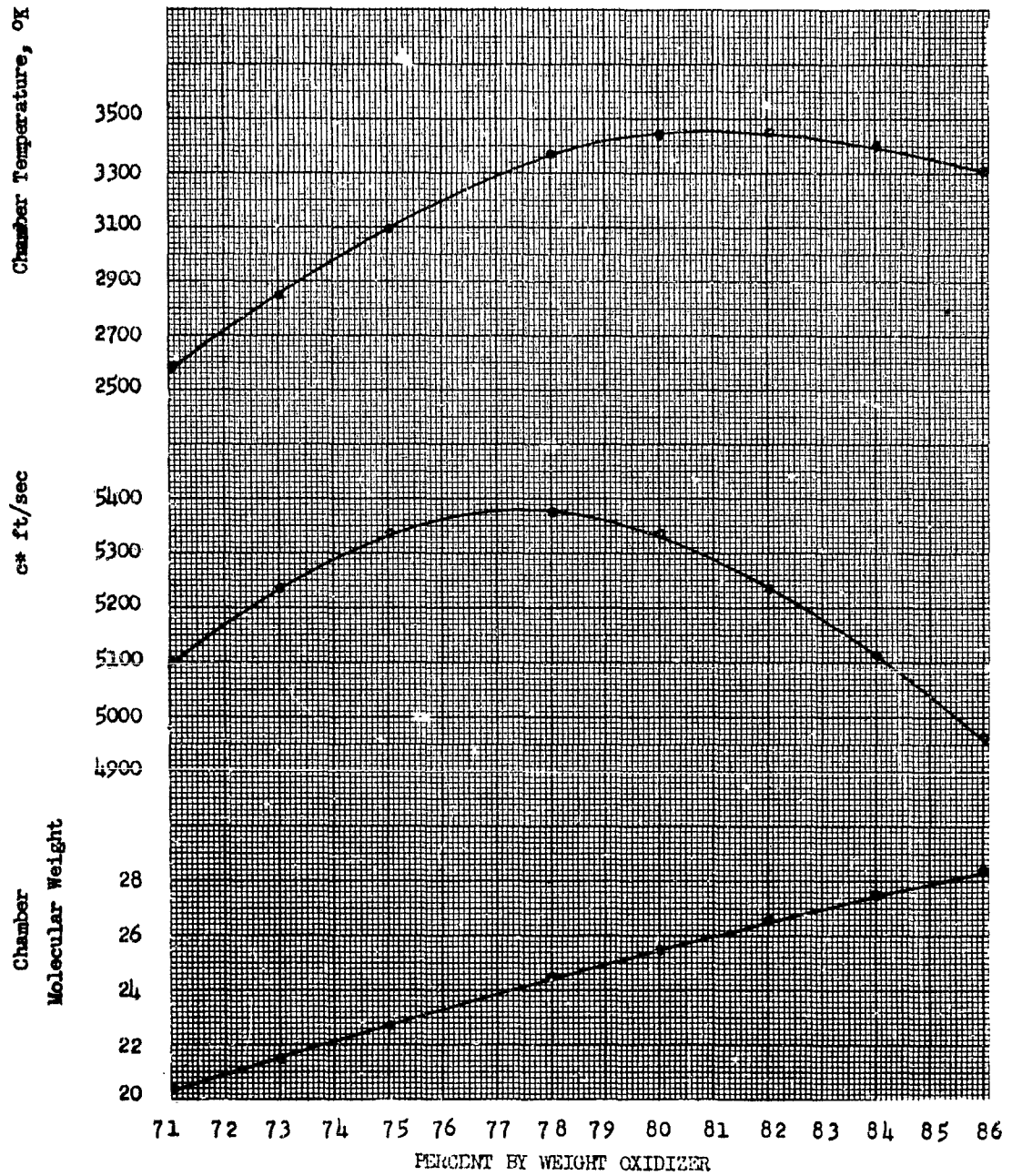
$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$

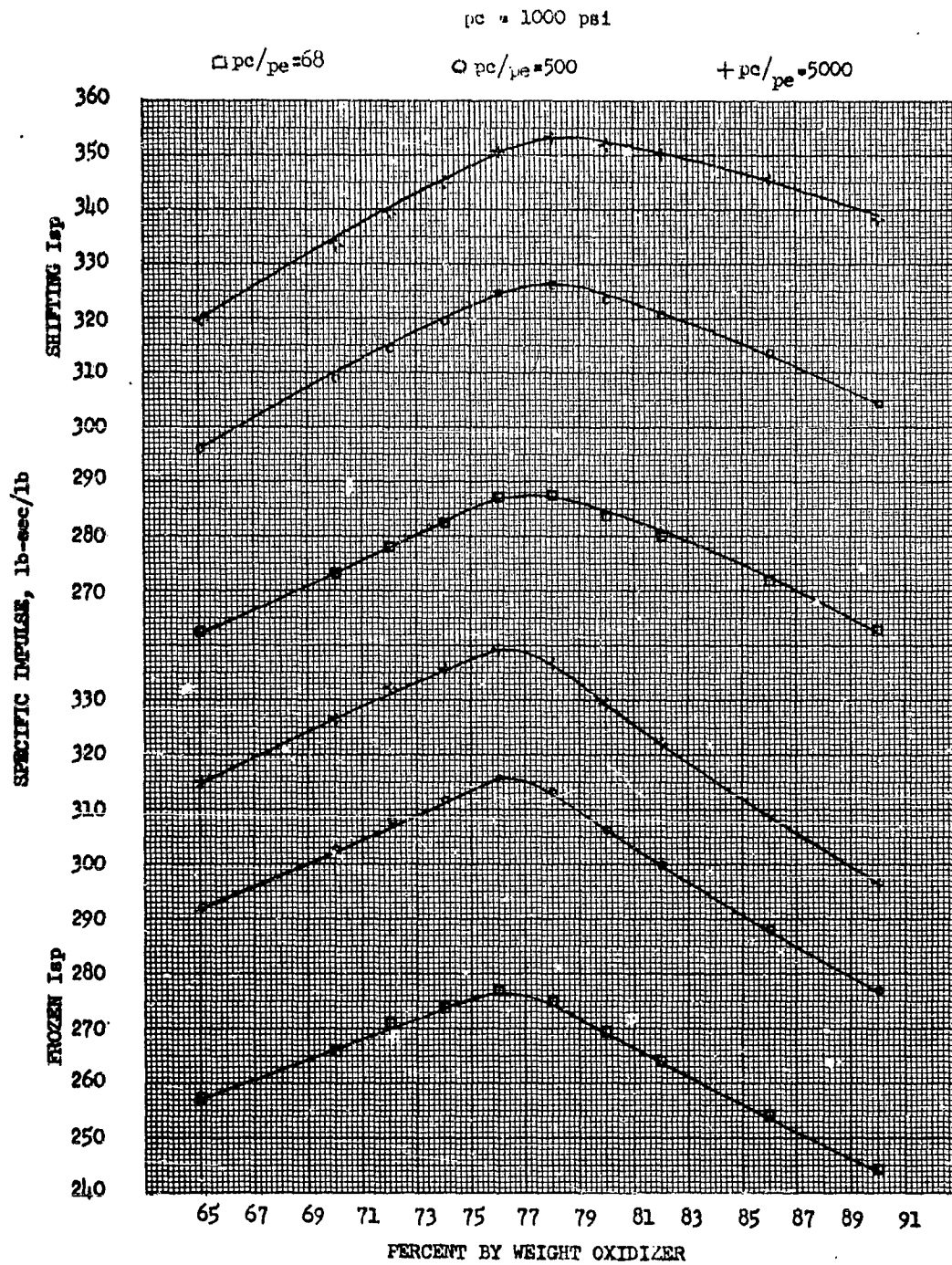




POLYETHYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 105



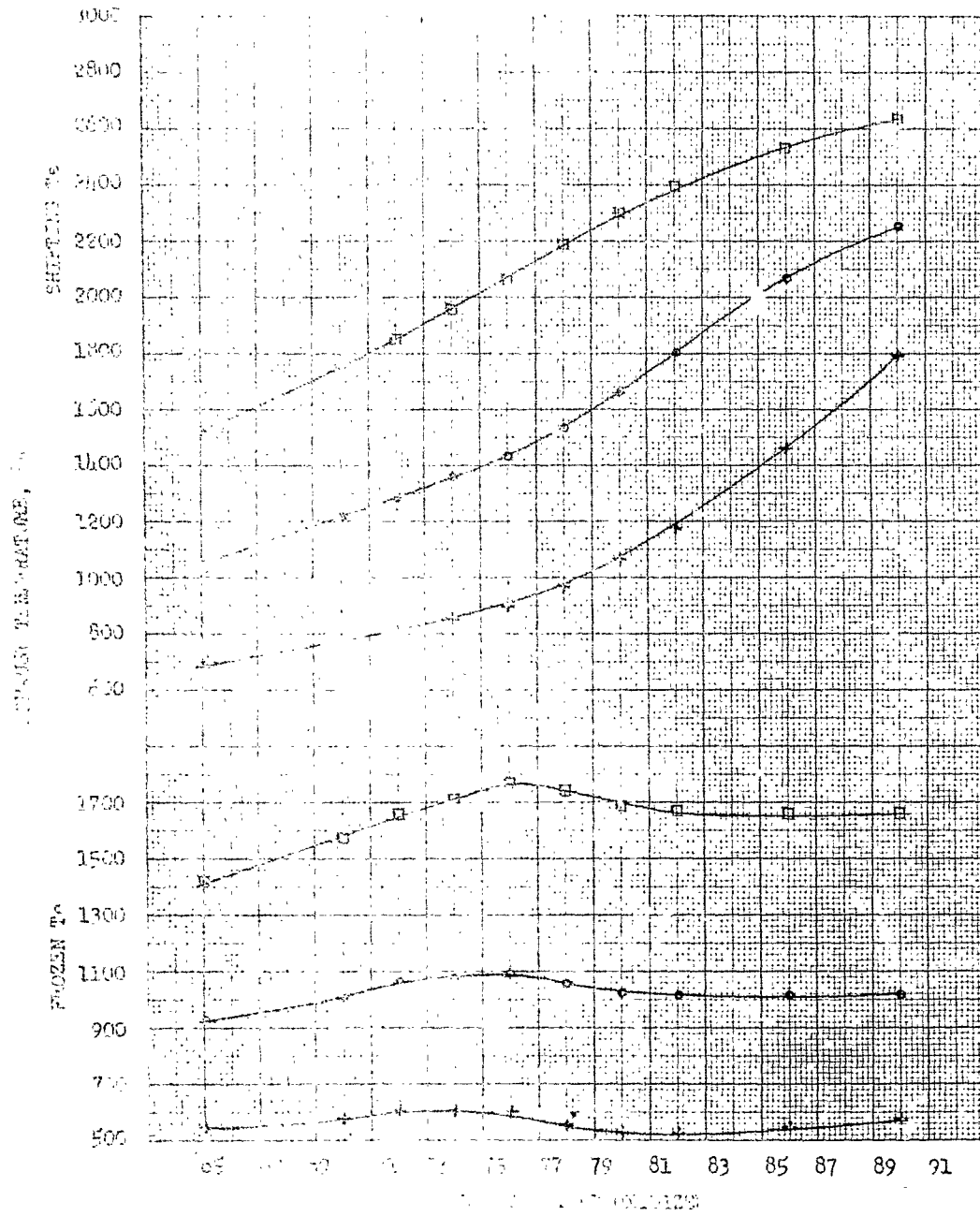
POLYETHYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 106

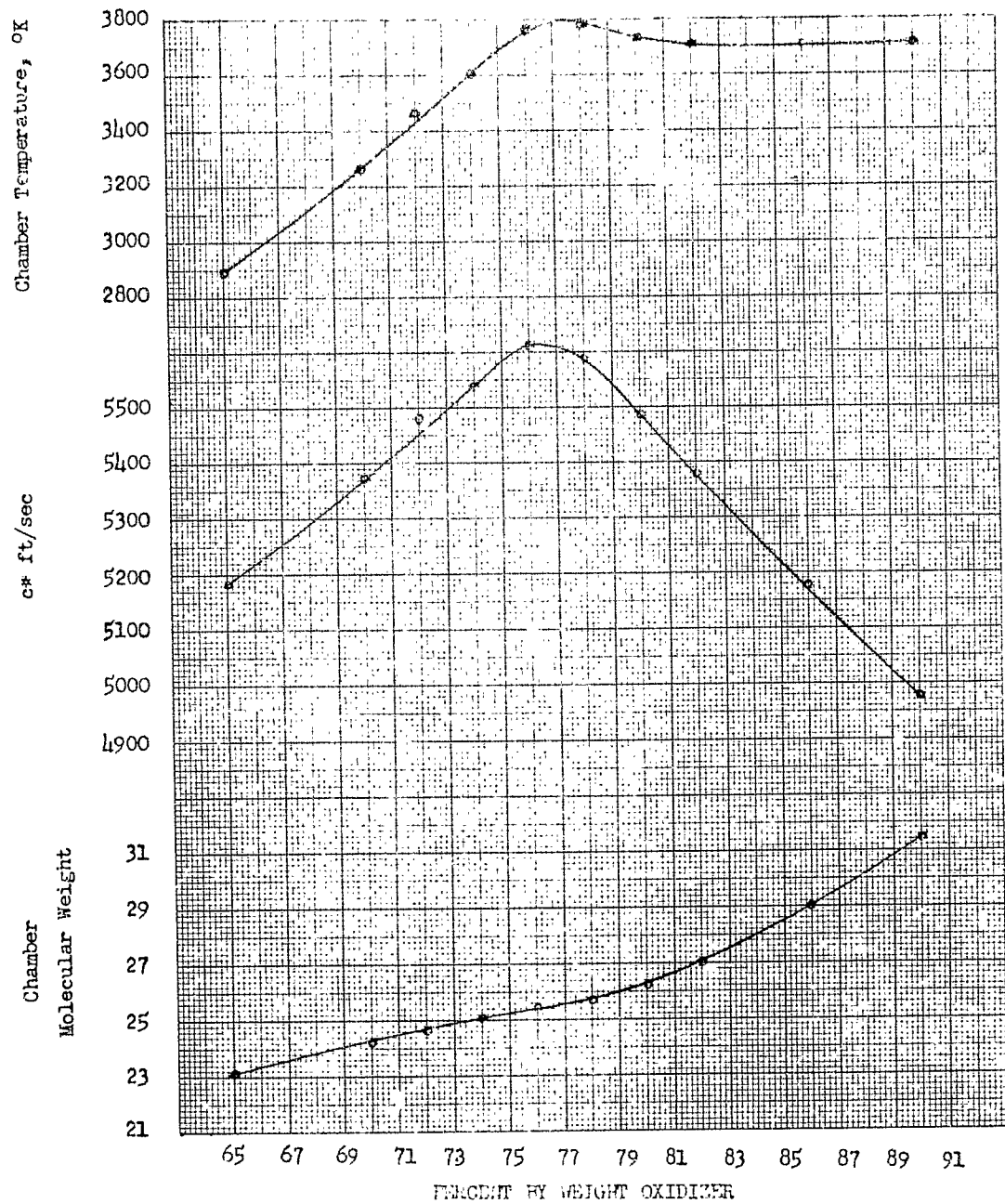


1981

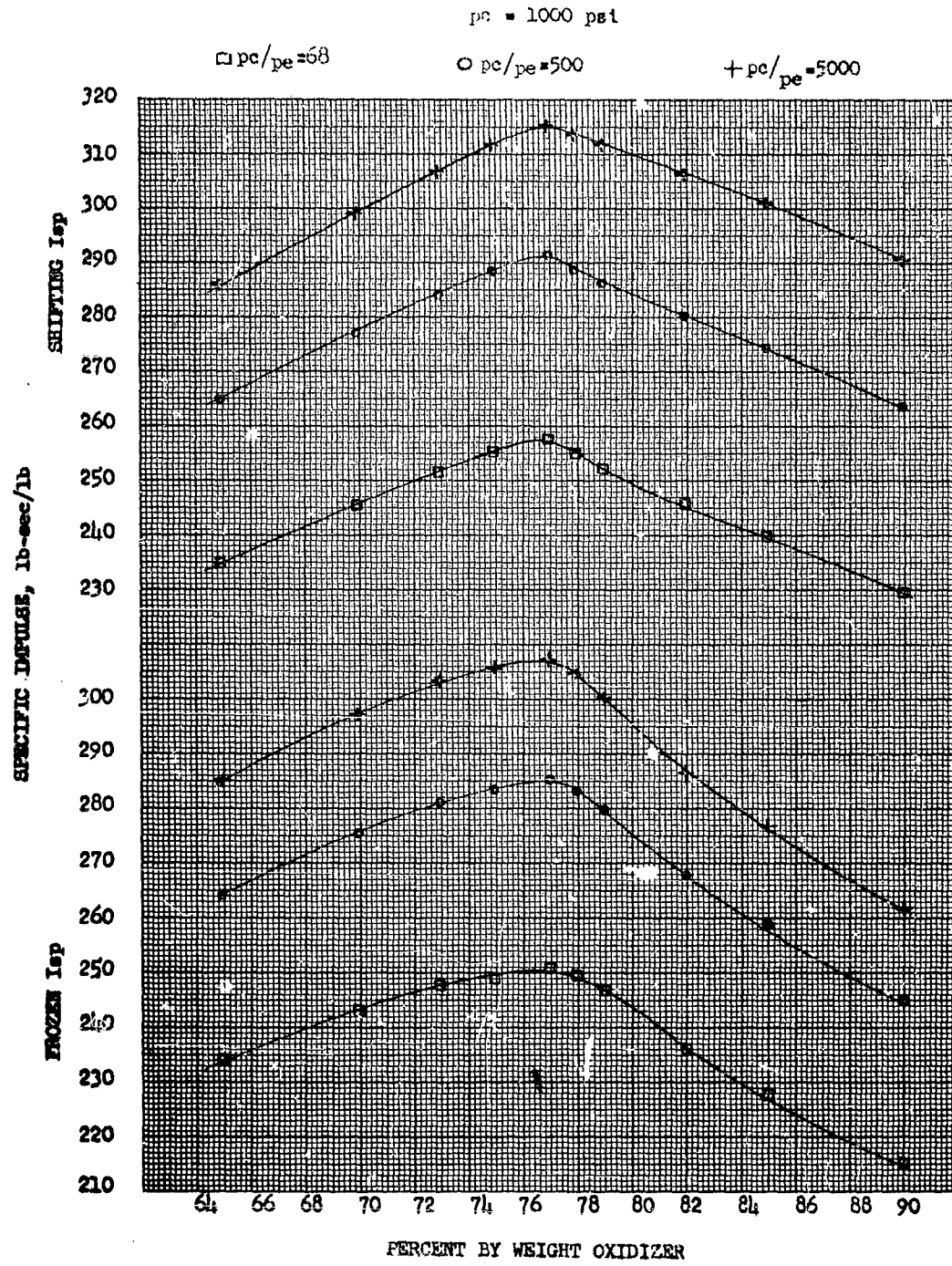
1981

1981

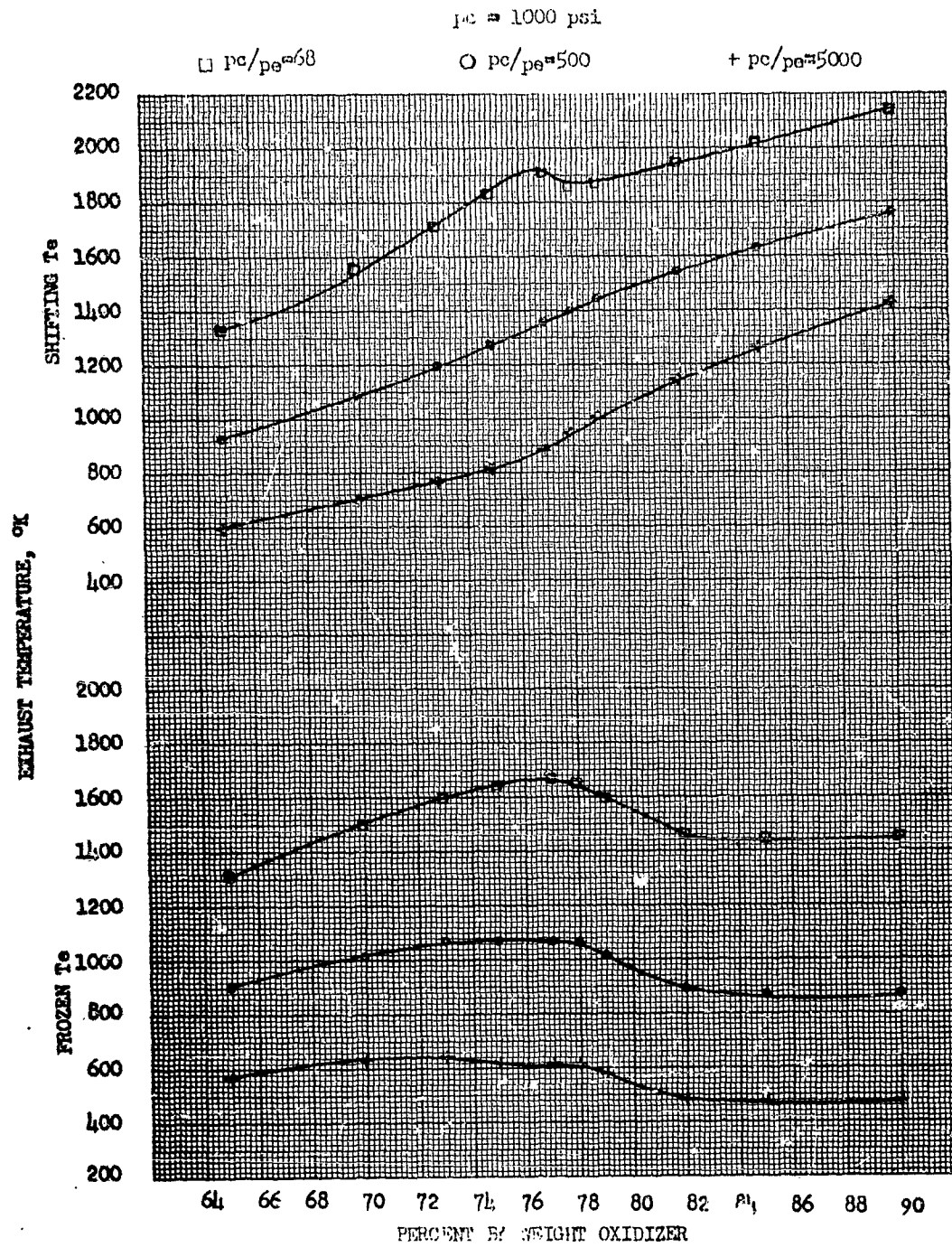




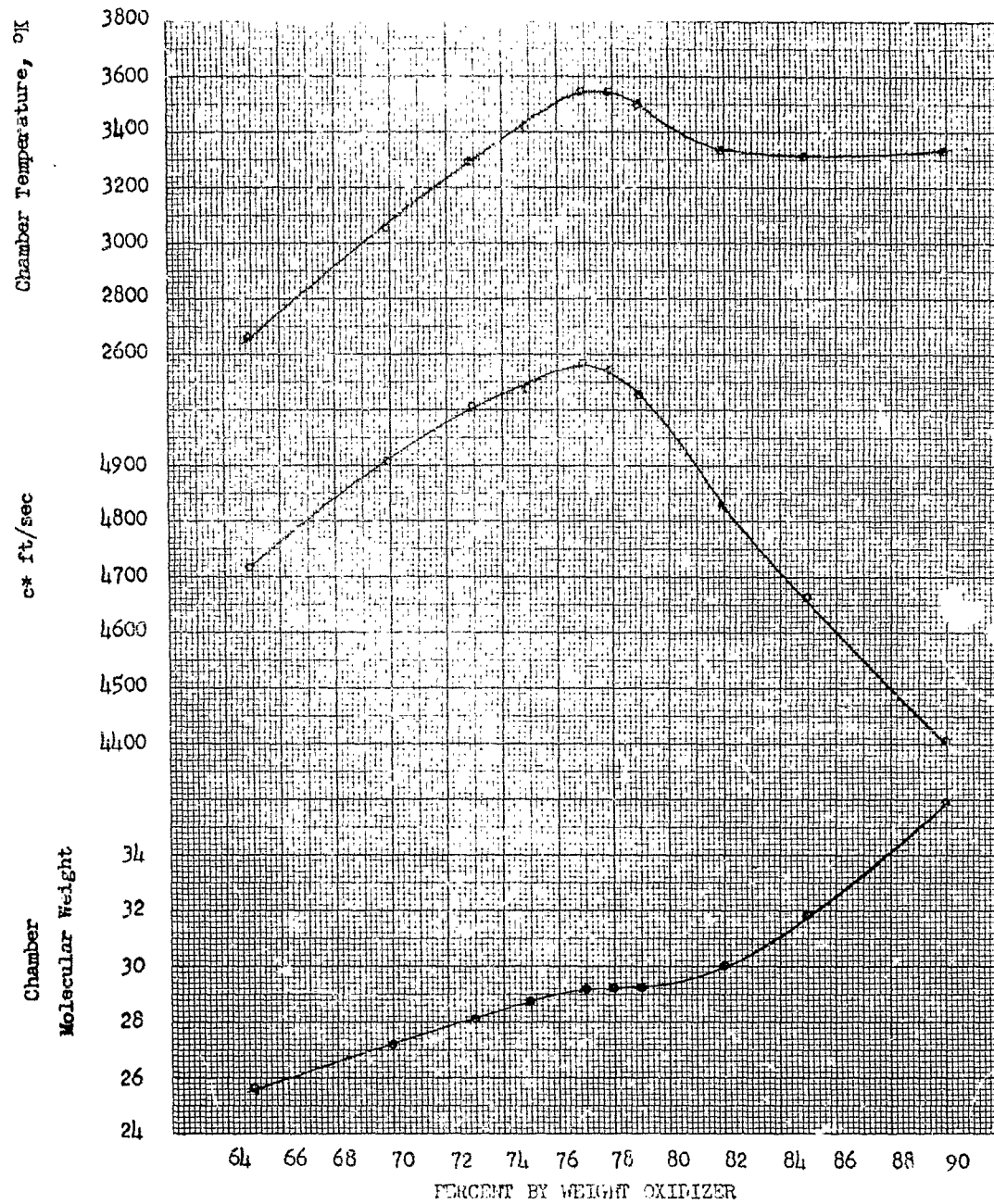
POLYETHYLENE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 109



POLYETHYLENE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 110



POLYETHYLENE CHAMBER PERFORMANCE CURVES FIGURE 111

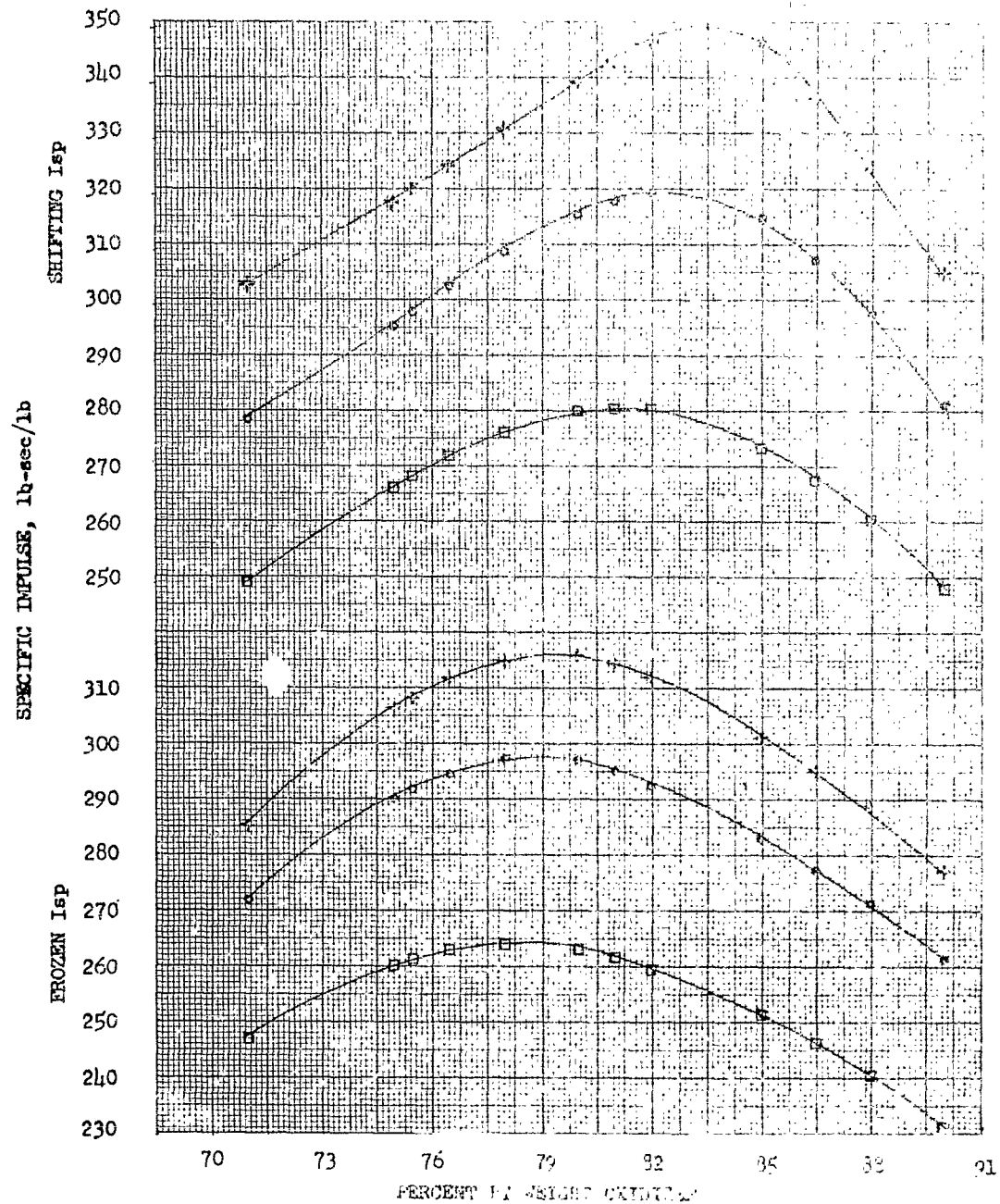


1000 psi

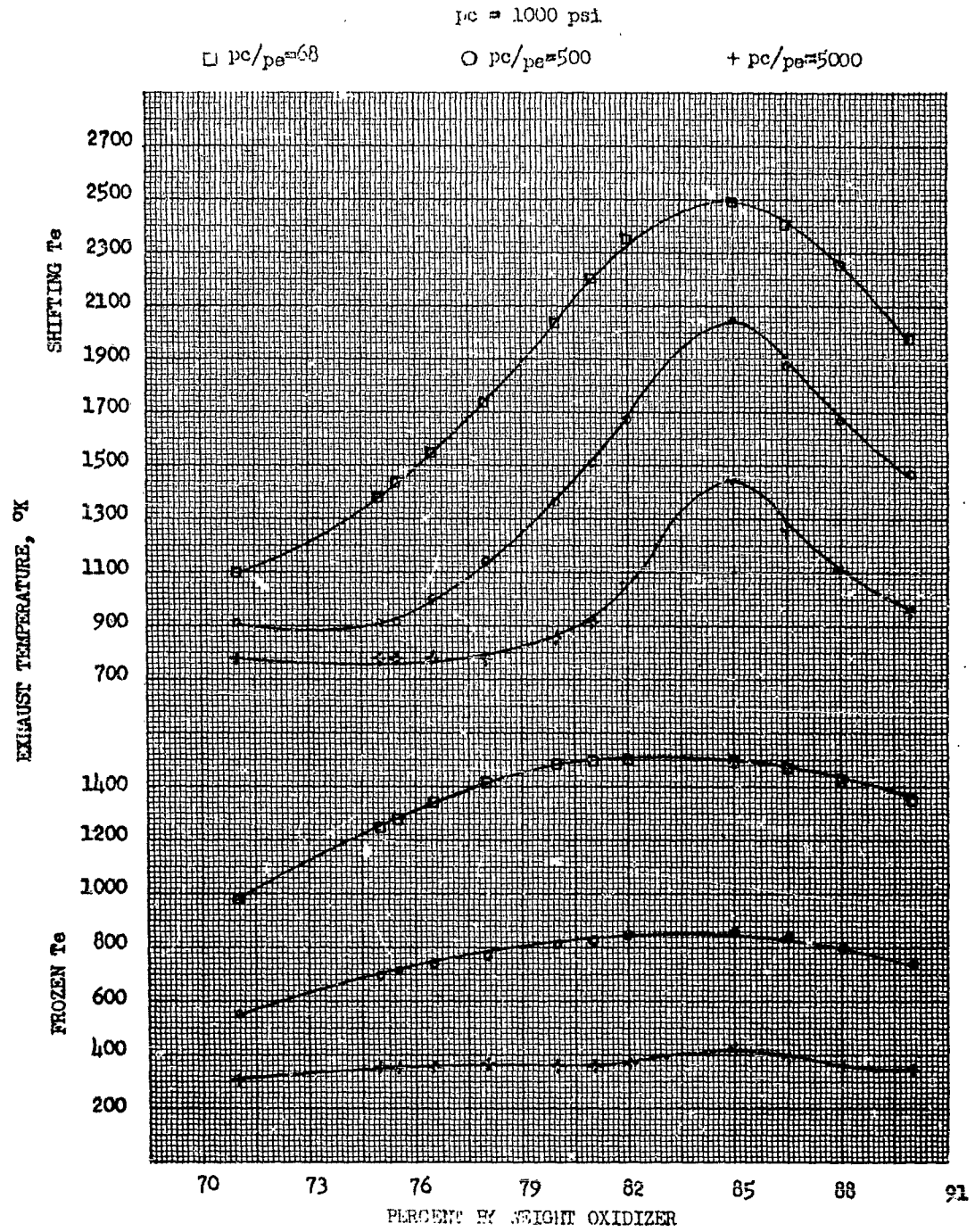
Cl₂/pe 200

Cl₂/pe 1000

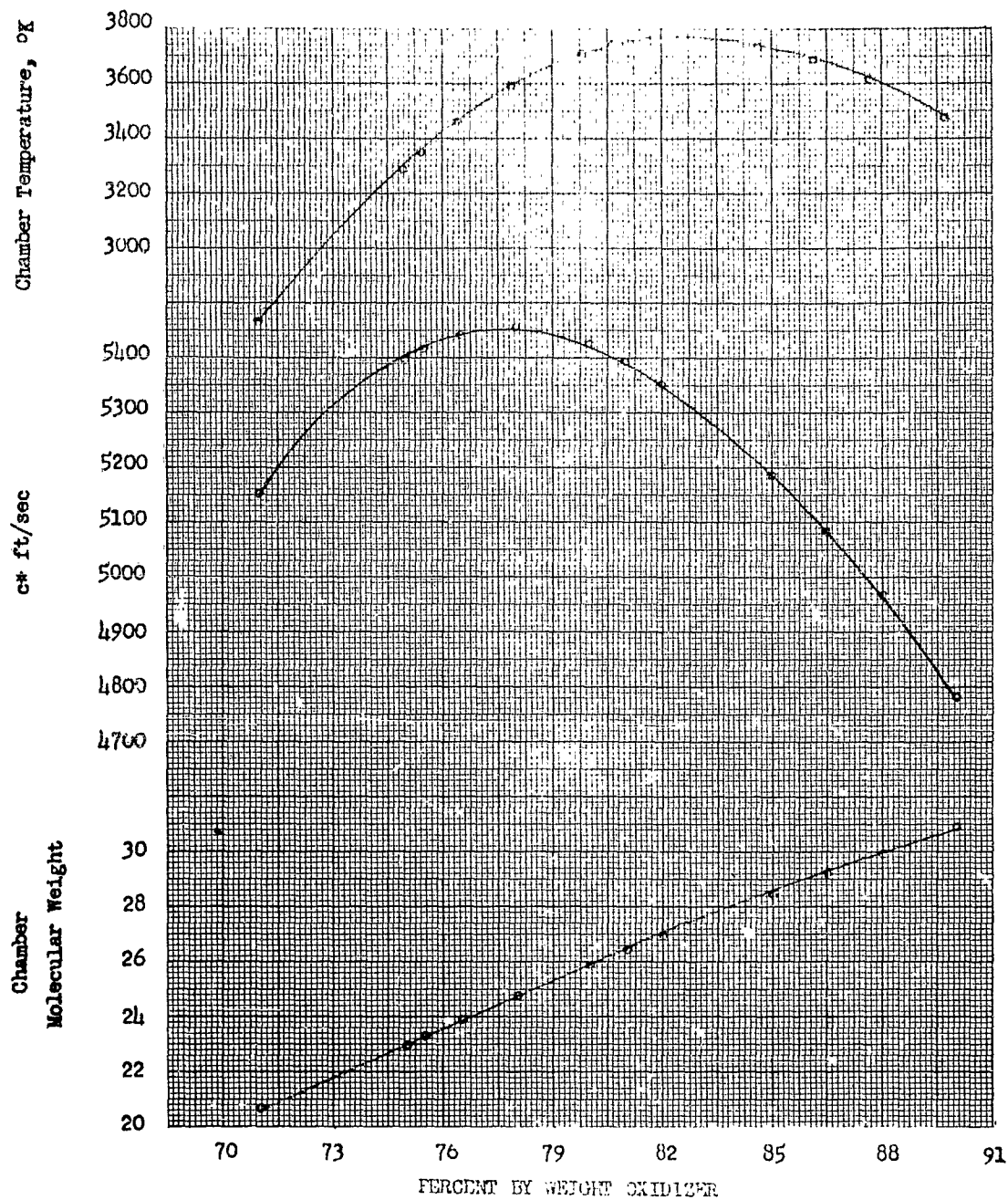
Cl₂/pe 1000



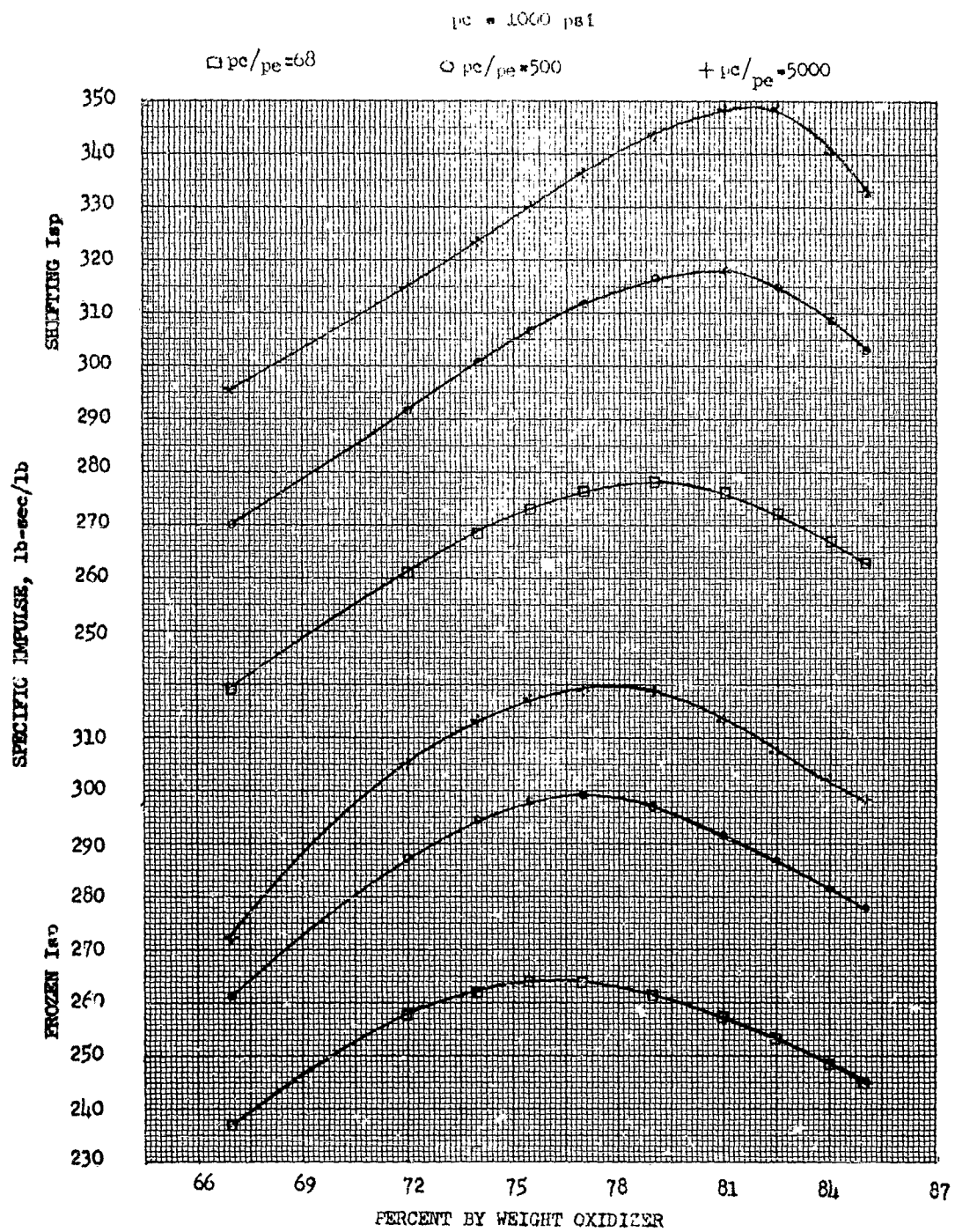
POLYETHYLENE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 113



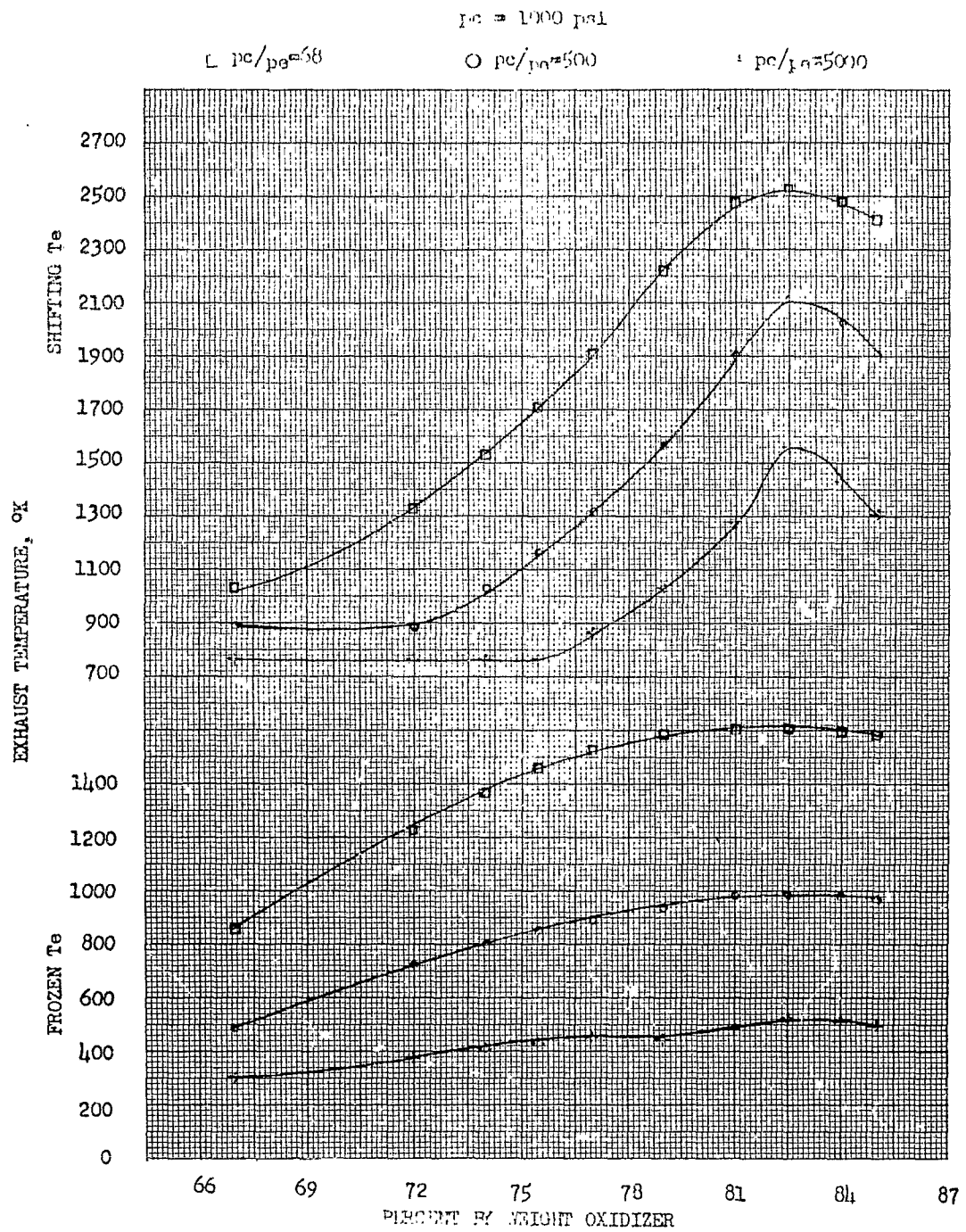
POLYETHYLENE - PERCHLORYL FLUORIDE COMBUSTION CURVES FIGURE 11A



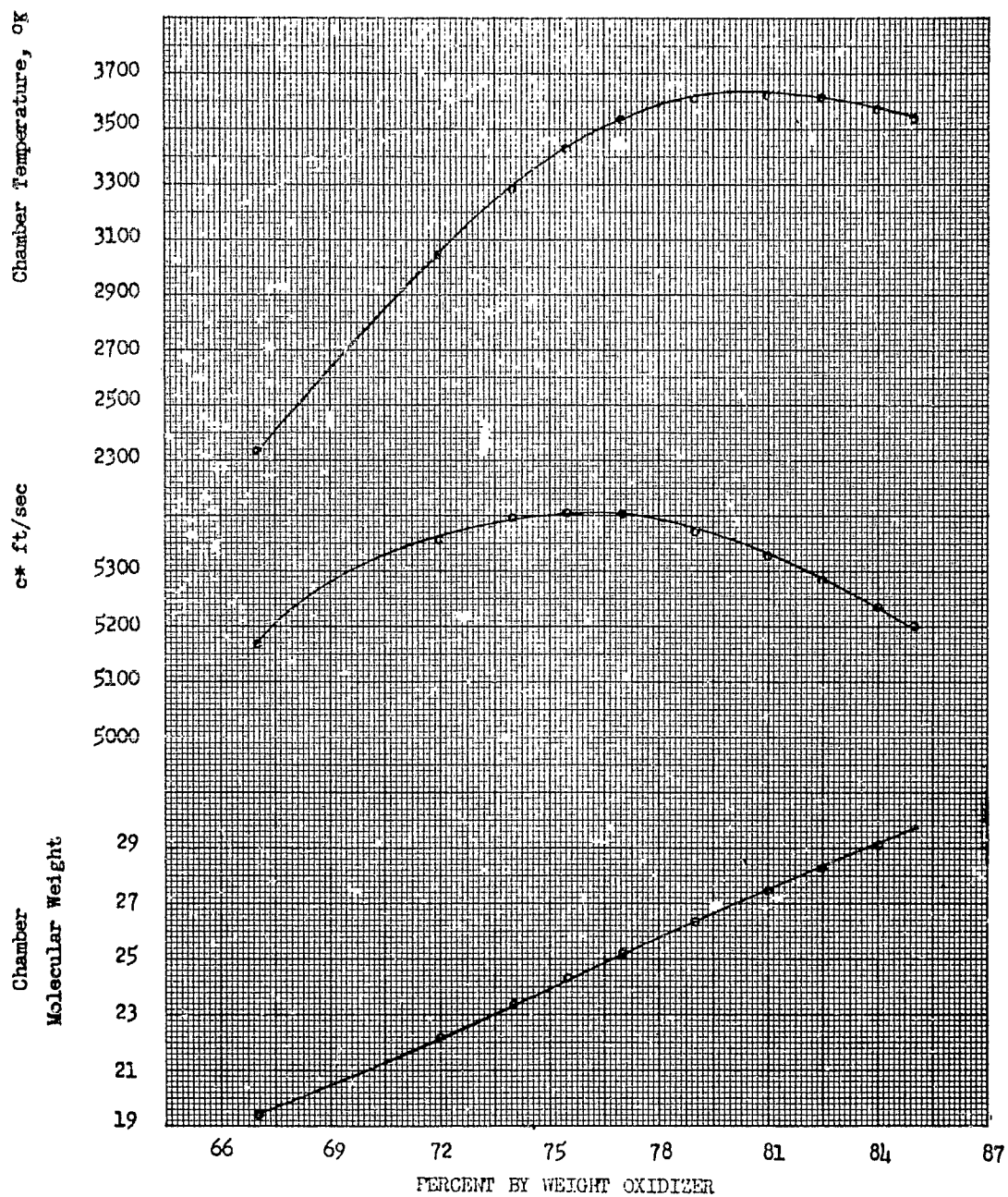
POLYETHYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 115



POLYETHYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 116



POLYETHYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 117



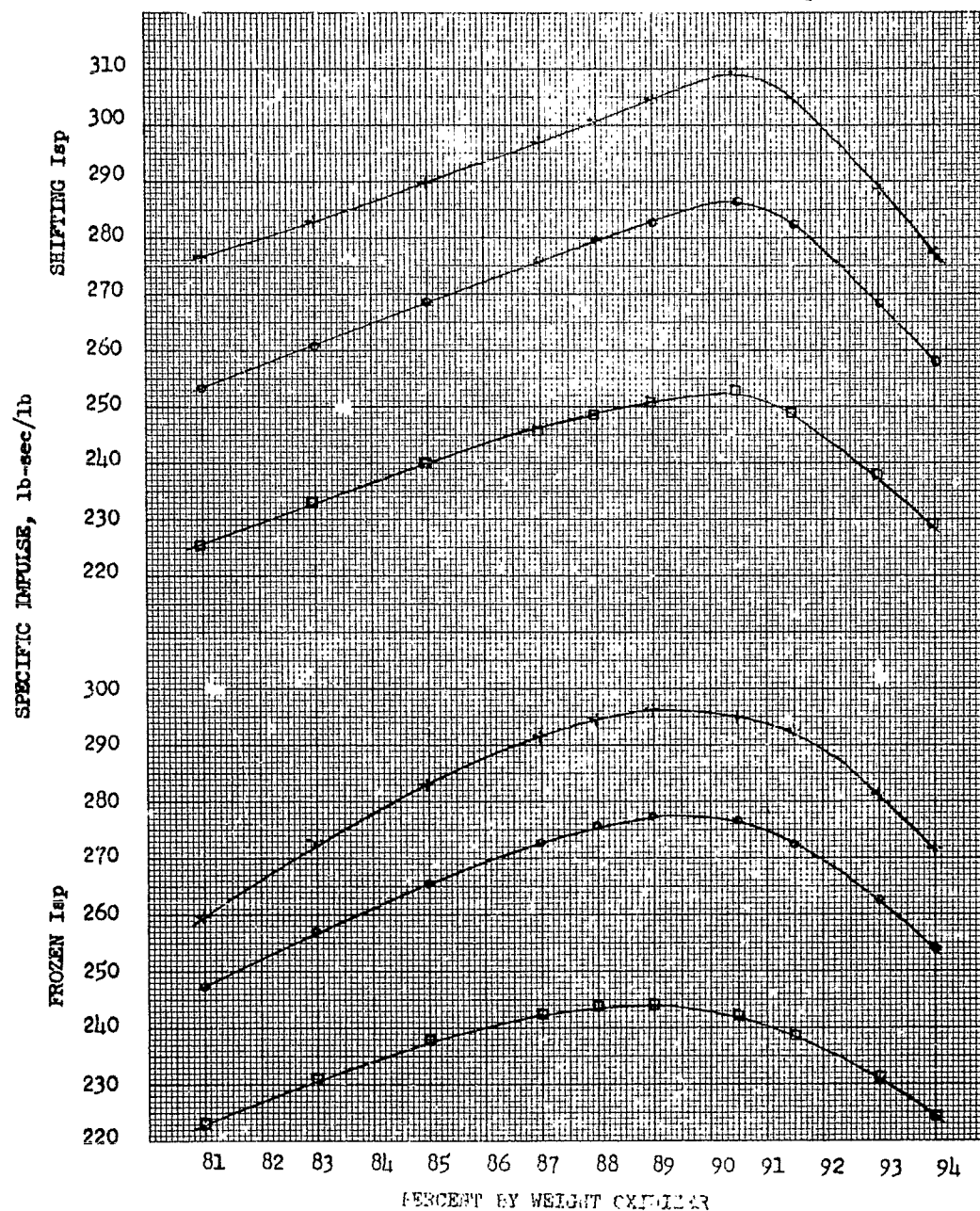
POLYETHYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 1.18

$p_c = 1000 \text{ psi}$

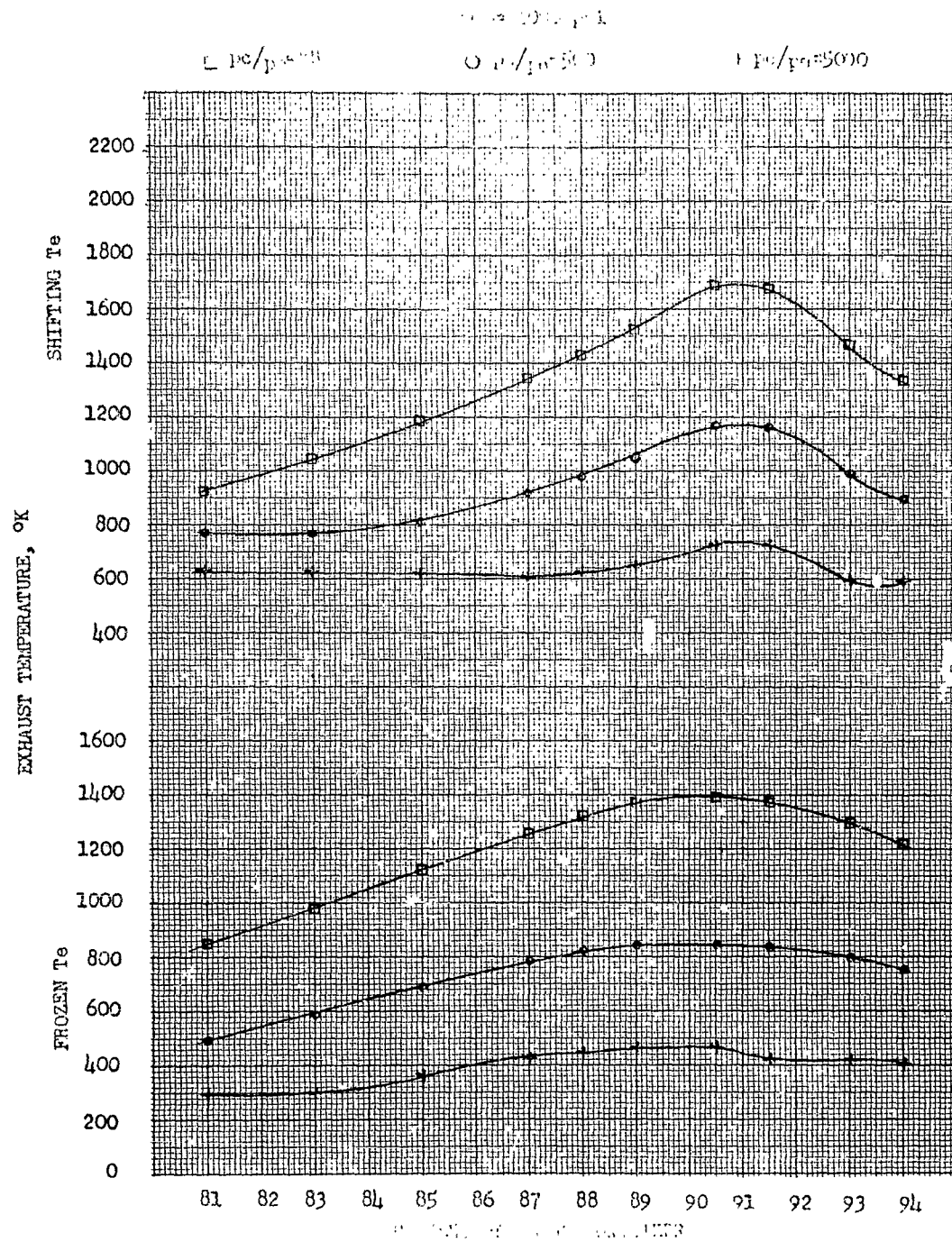
$\square p_c/p_e = 0.8$

$\circ p_c/p_e = 500$

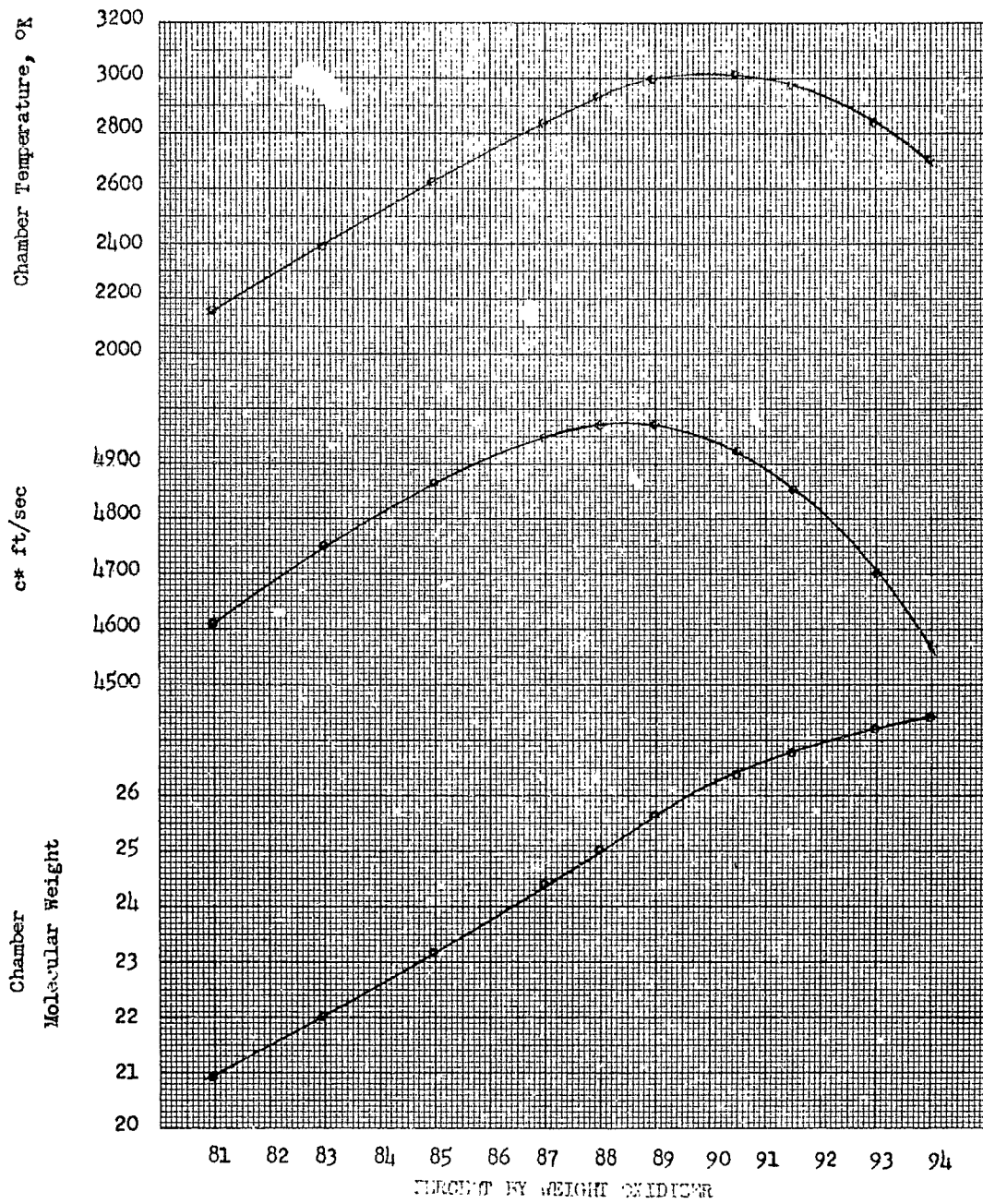
$+ p_c/p_e = 5000$



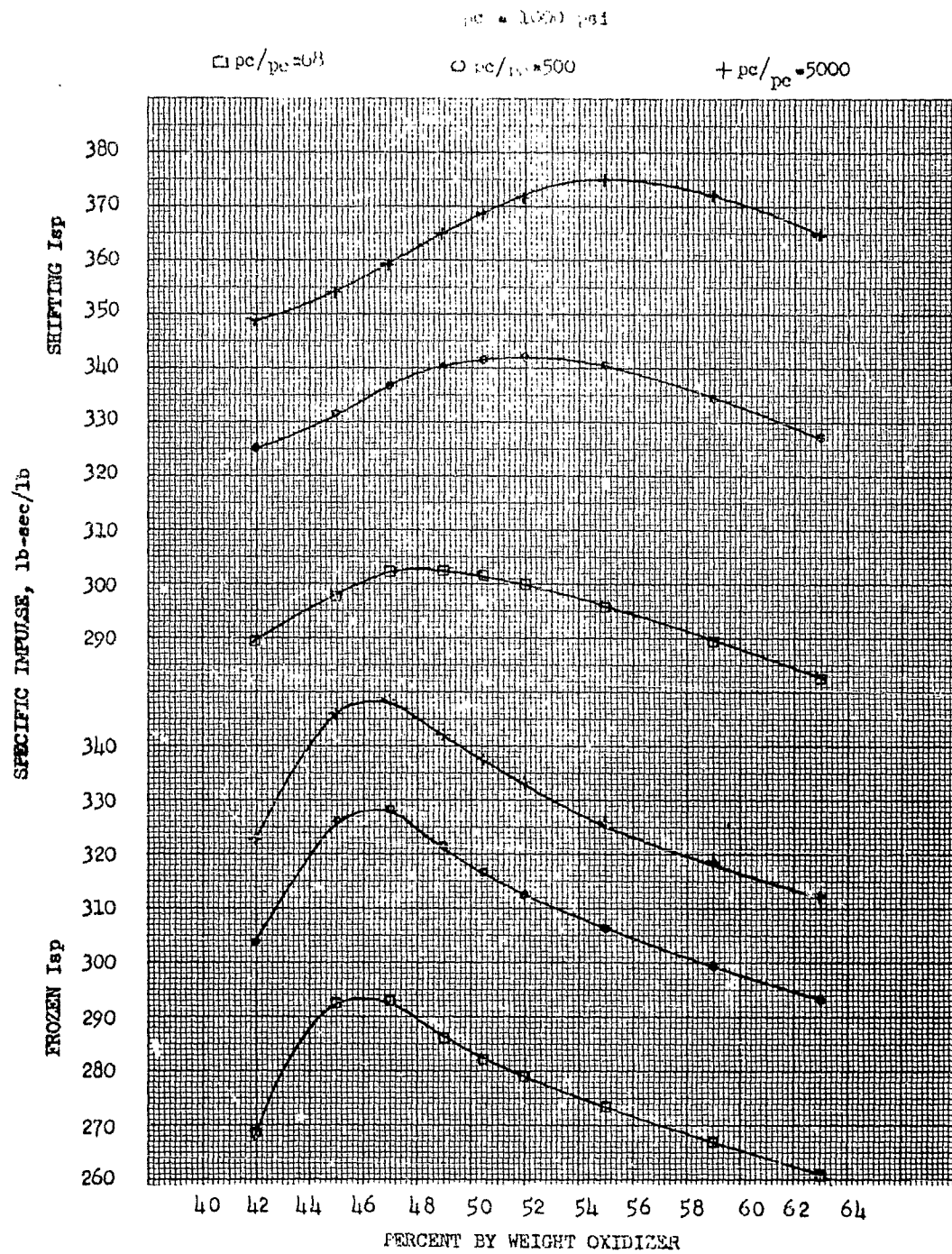
POLYETHYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 119

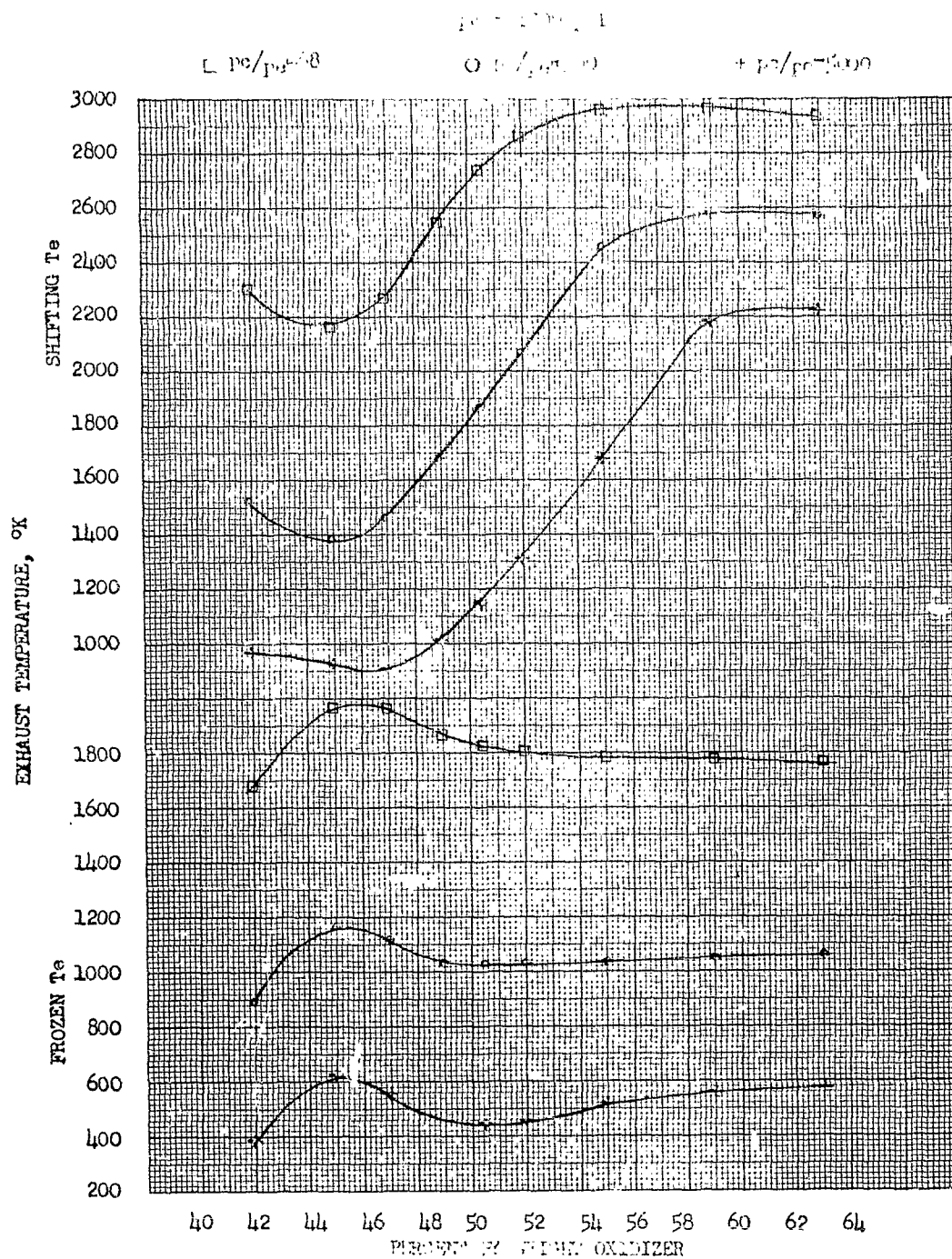


POLYETHYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 120

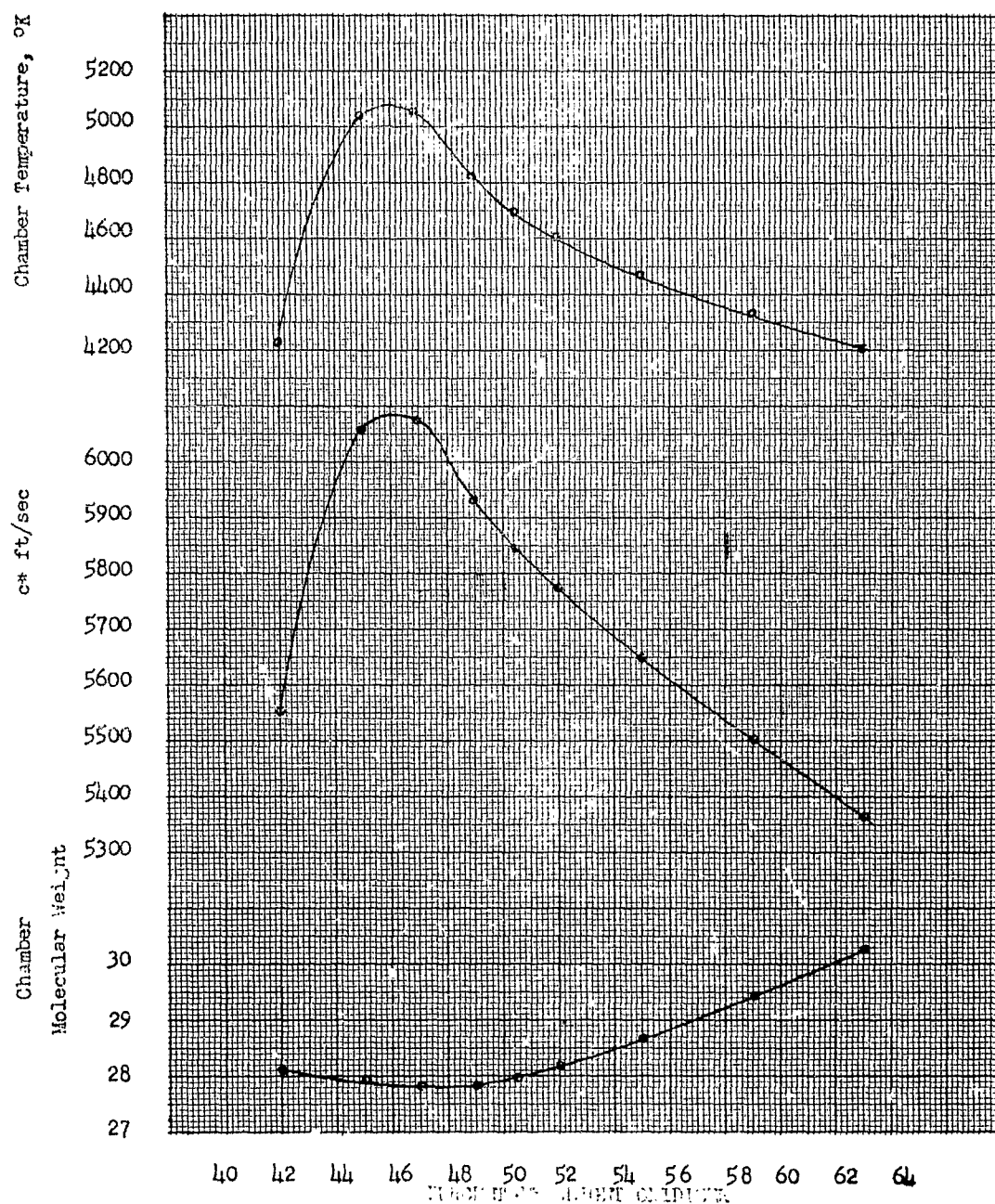


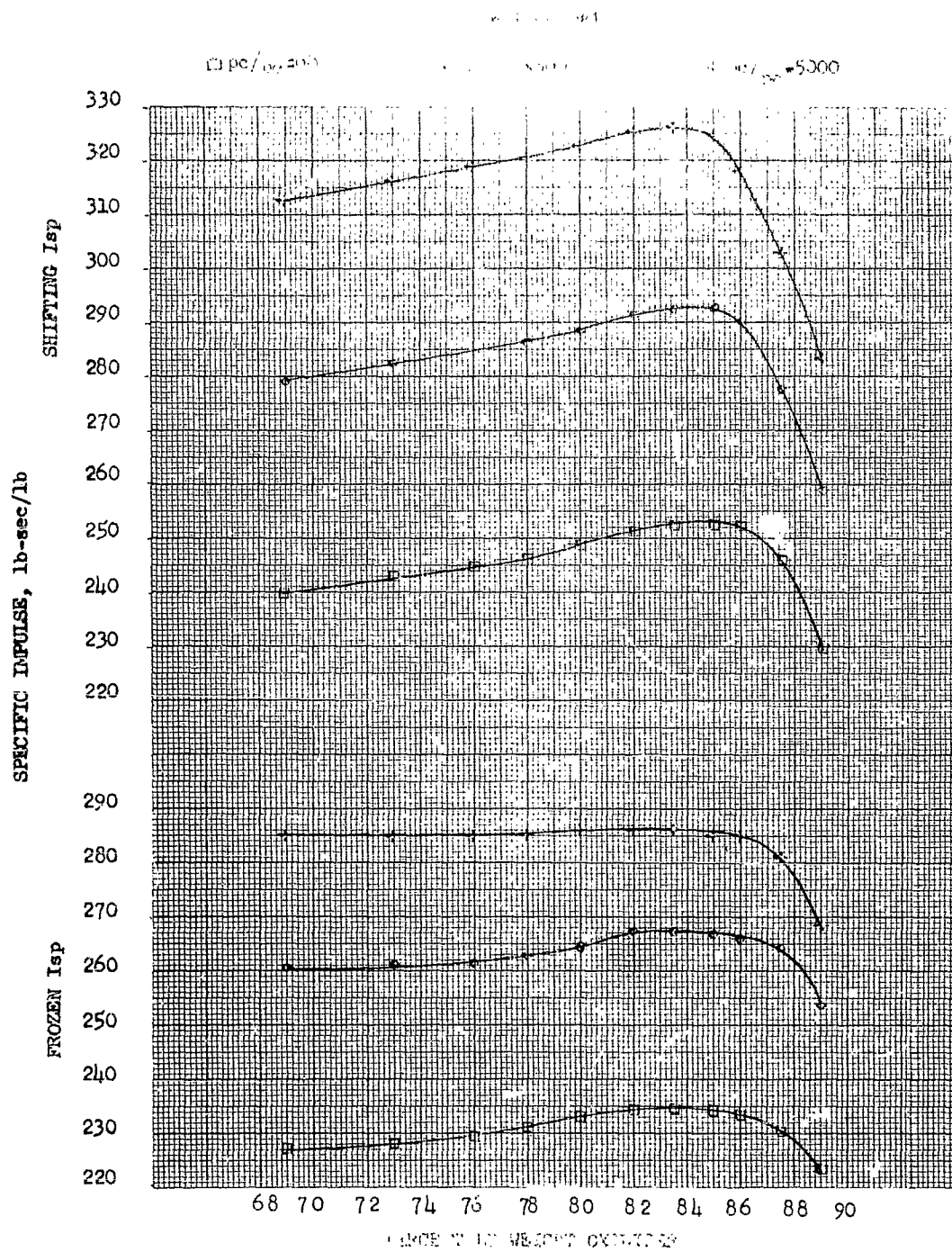
DICYANOACETYLENE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 121

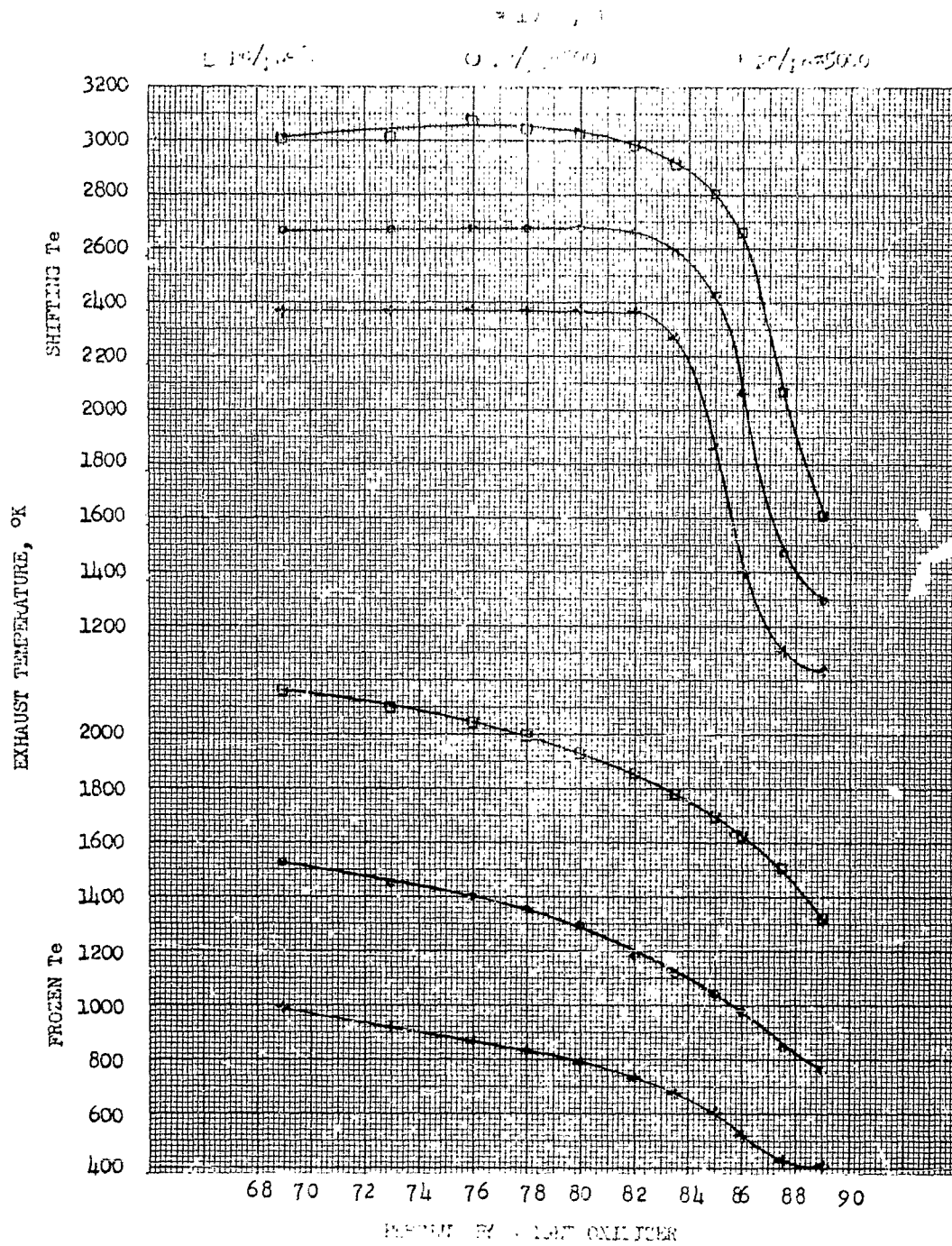




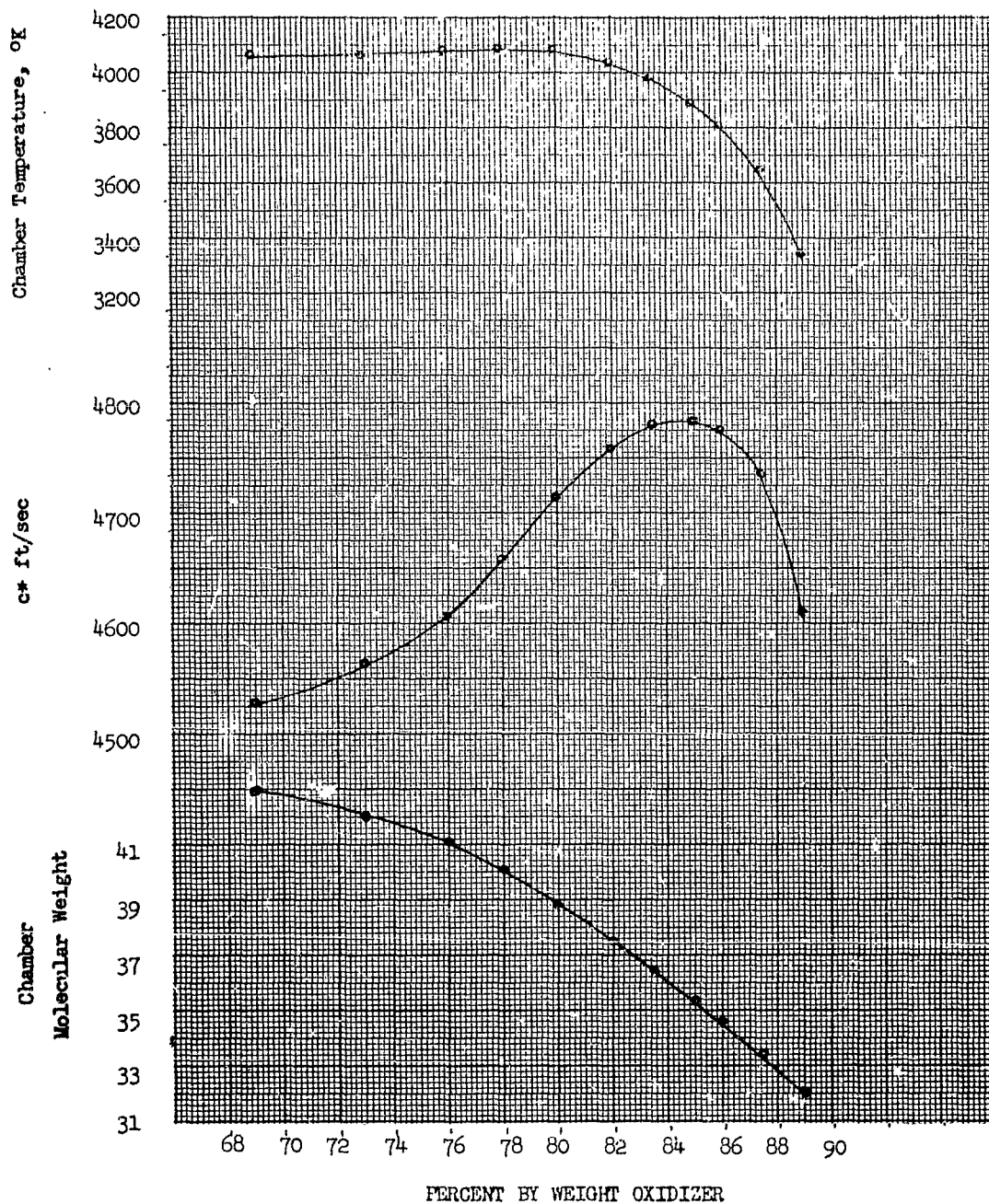
DICYANOACETYLENE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 123







DICYANOACETYLENE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 126



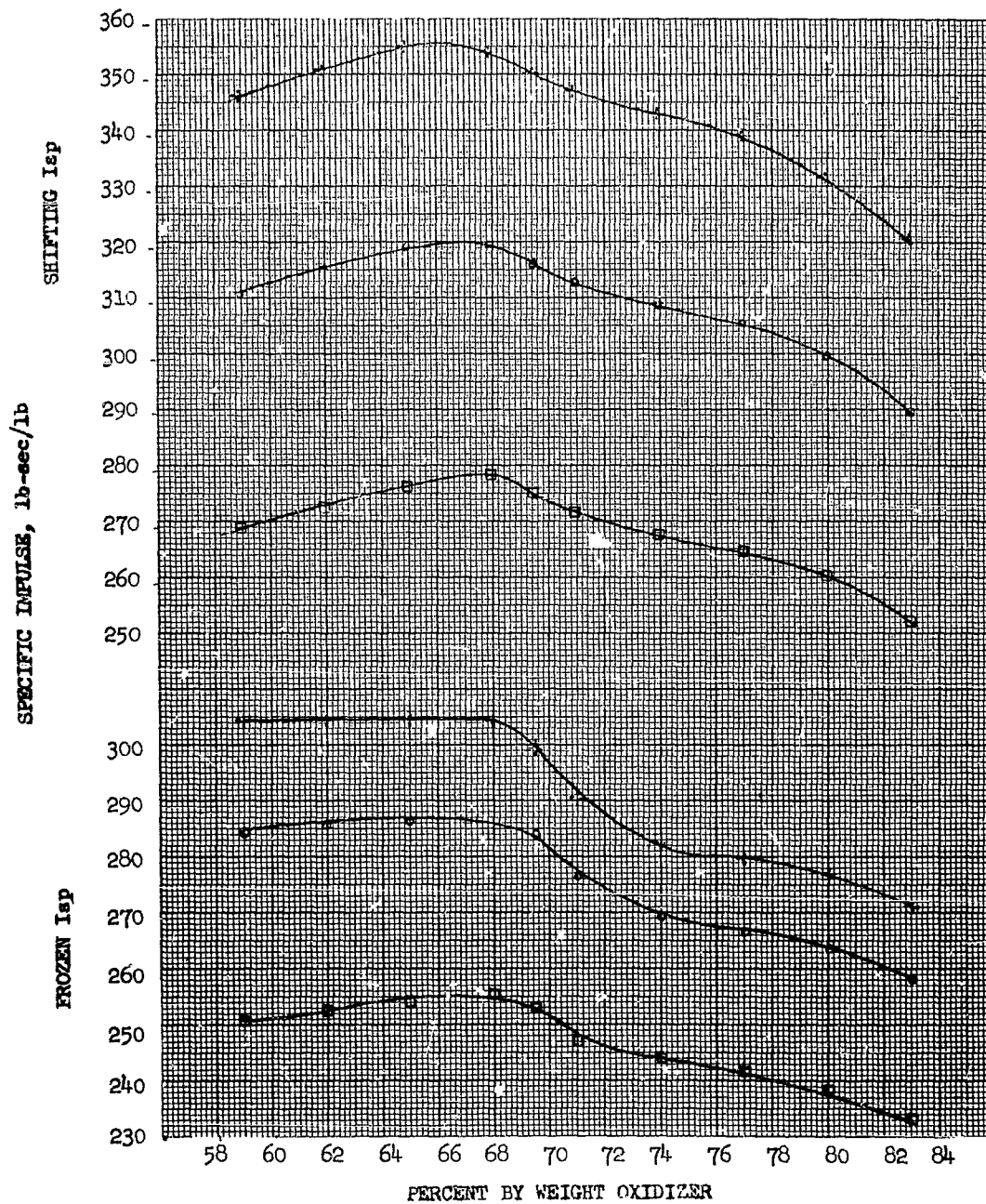
DICYANOACETYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 127

$p_c = 1000 \text{ psi}$

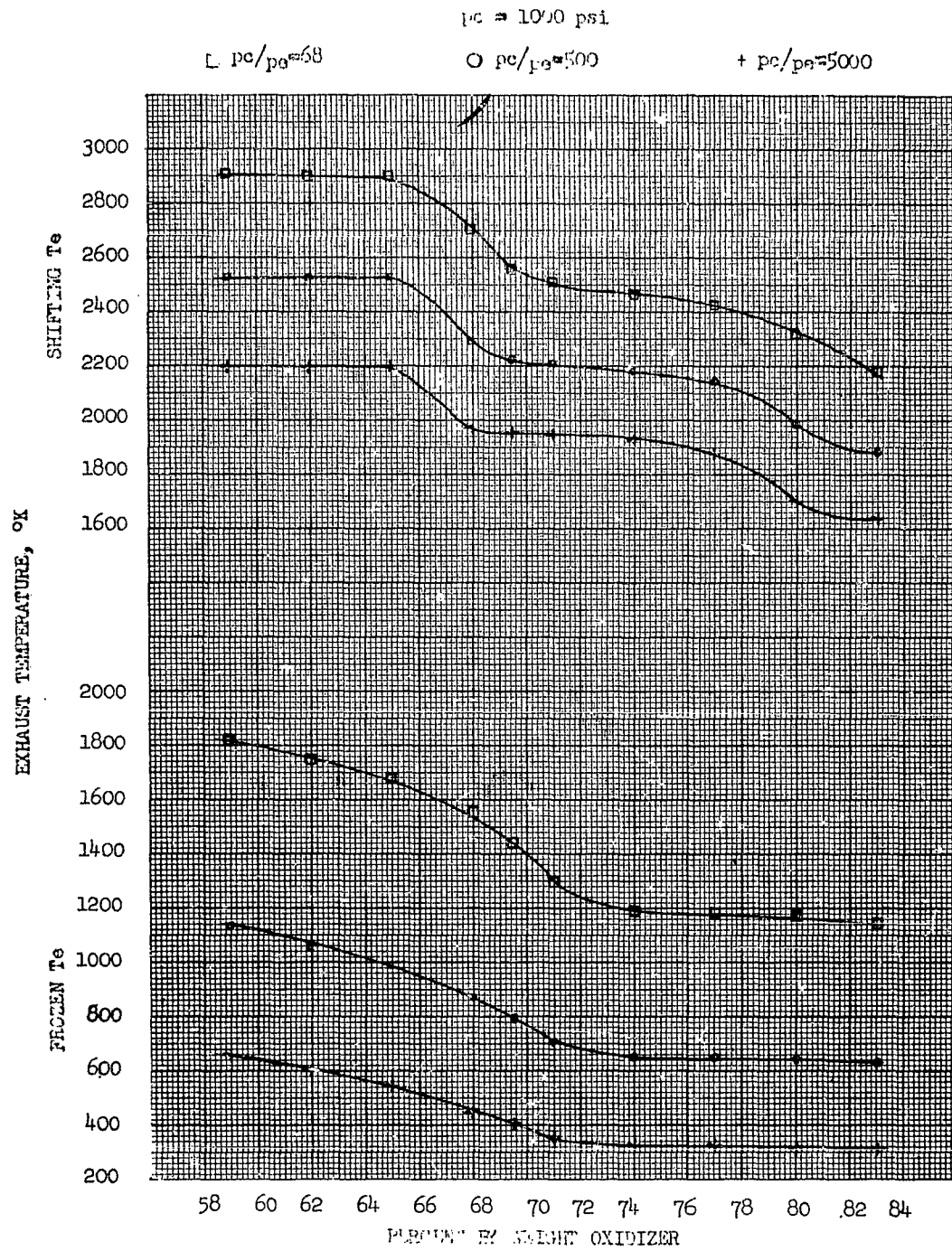
$\square p_c/p_e = 0.8$

$\circ p_c/p_e = 500$

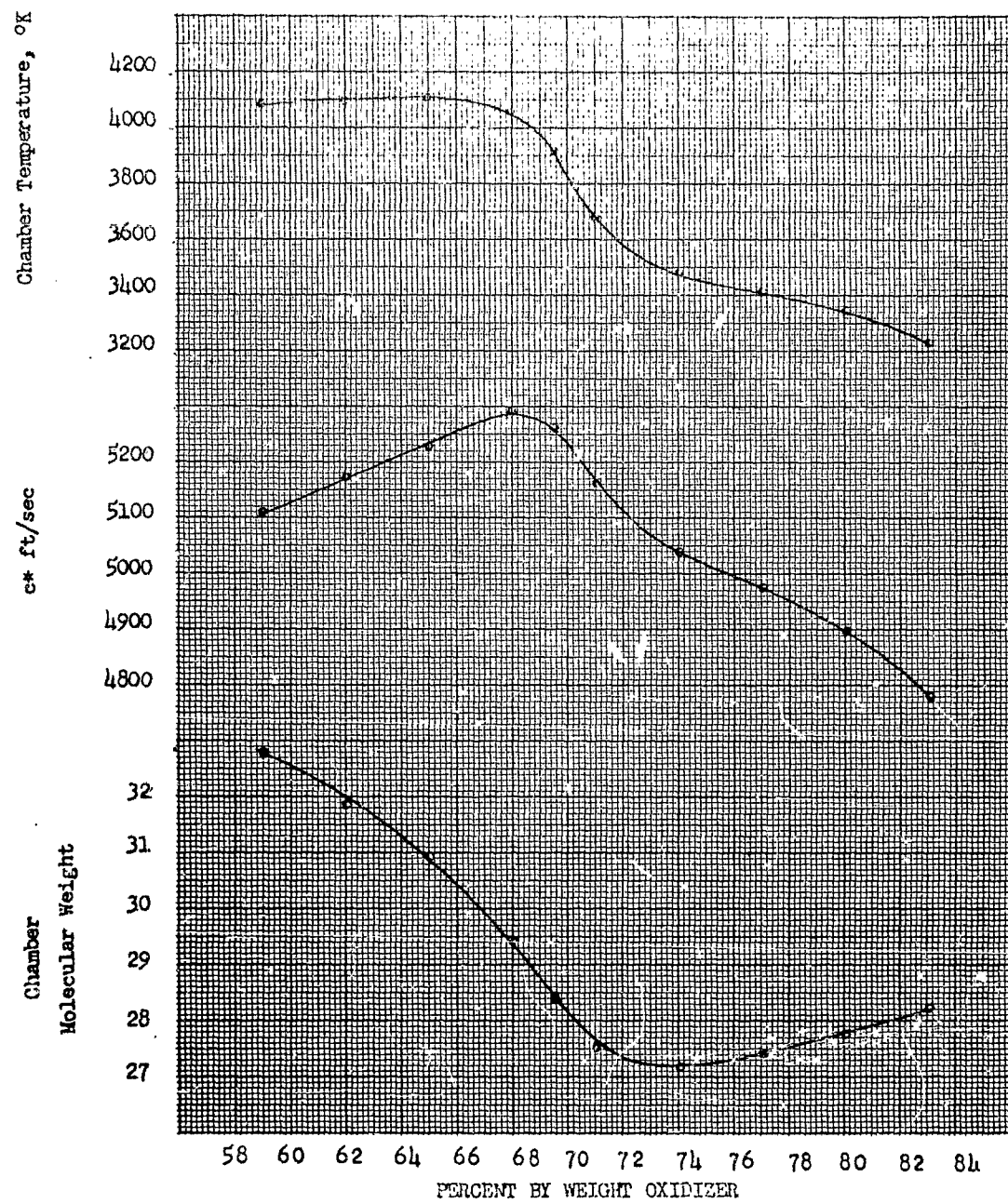
$+ p_c/p_e = 5000$



DICYANOACETYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 128



DICYANOACETYLENE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 129



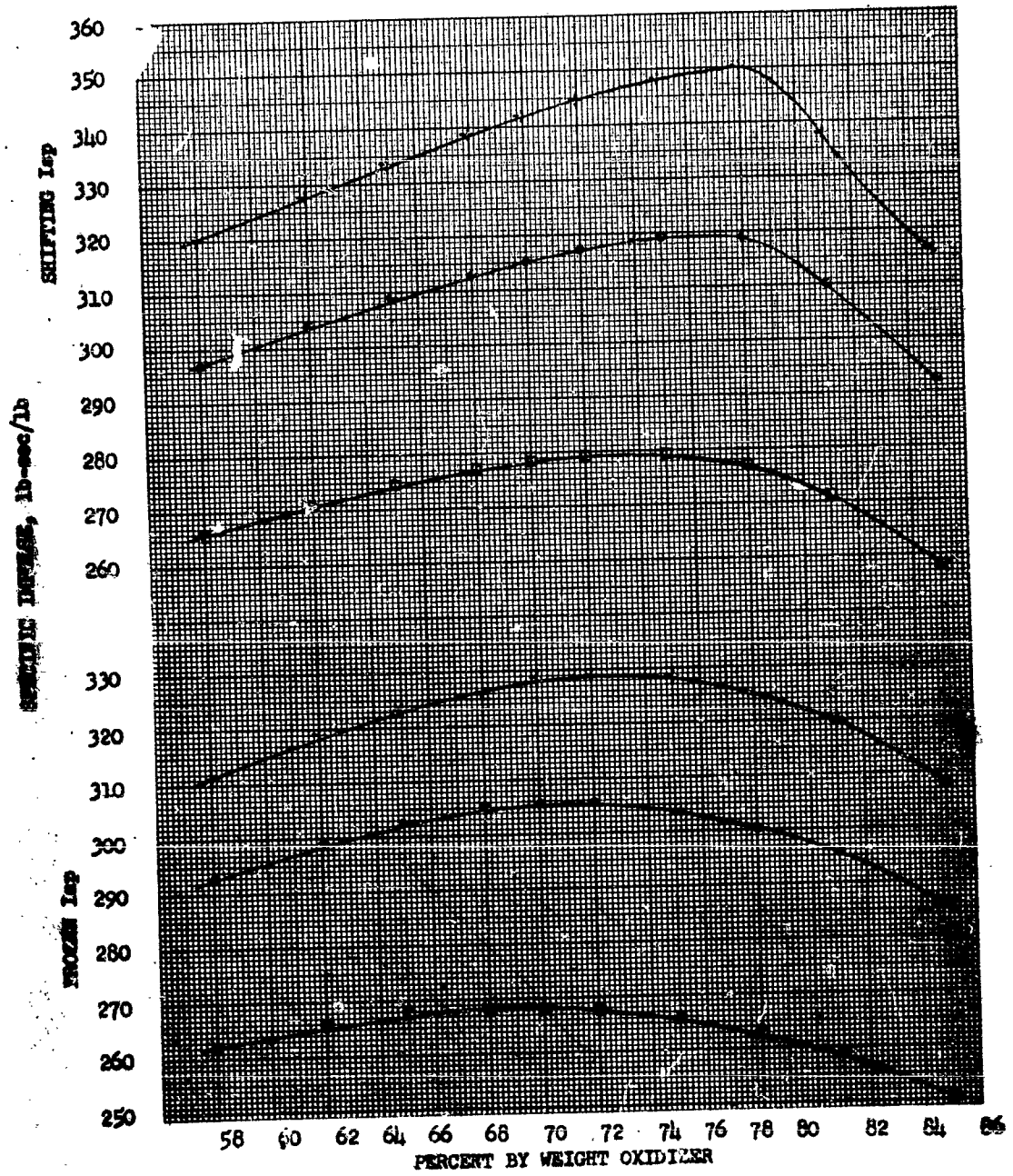
DICYANOACETYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 130

pc = 1000 psi

□ pc/pe = 68

○ pc/pe = 500

+ pc/pe = 5000



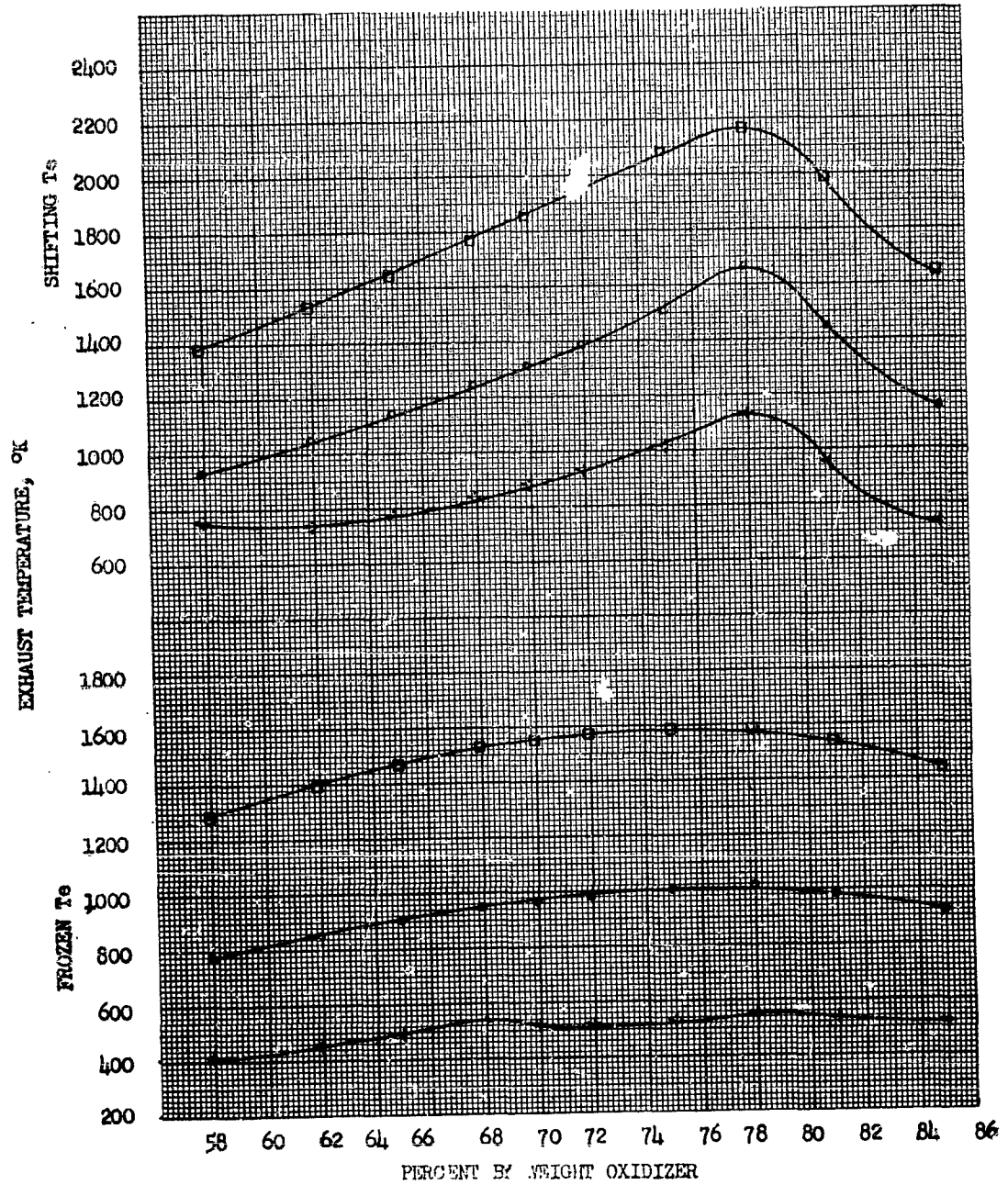
DICYANOACETYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 131

$p_c = 1000$ psi

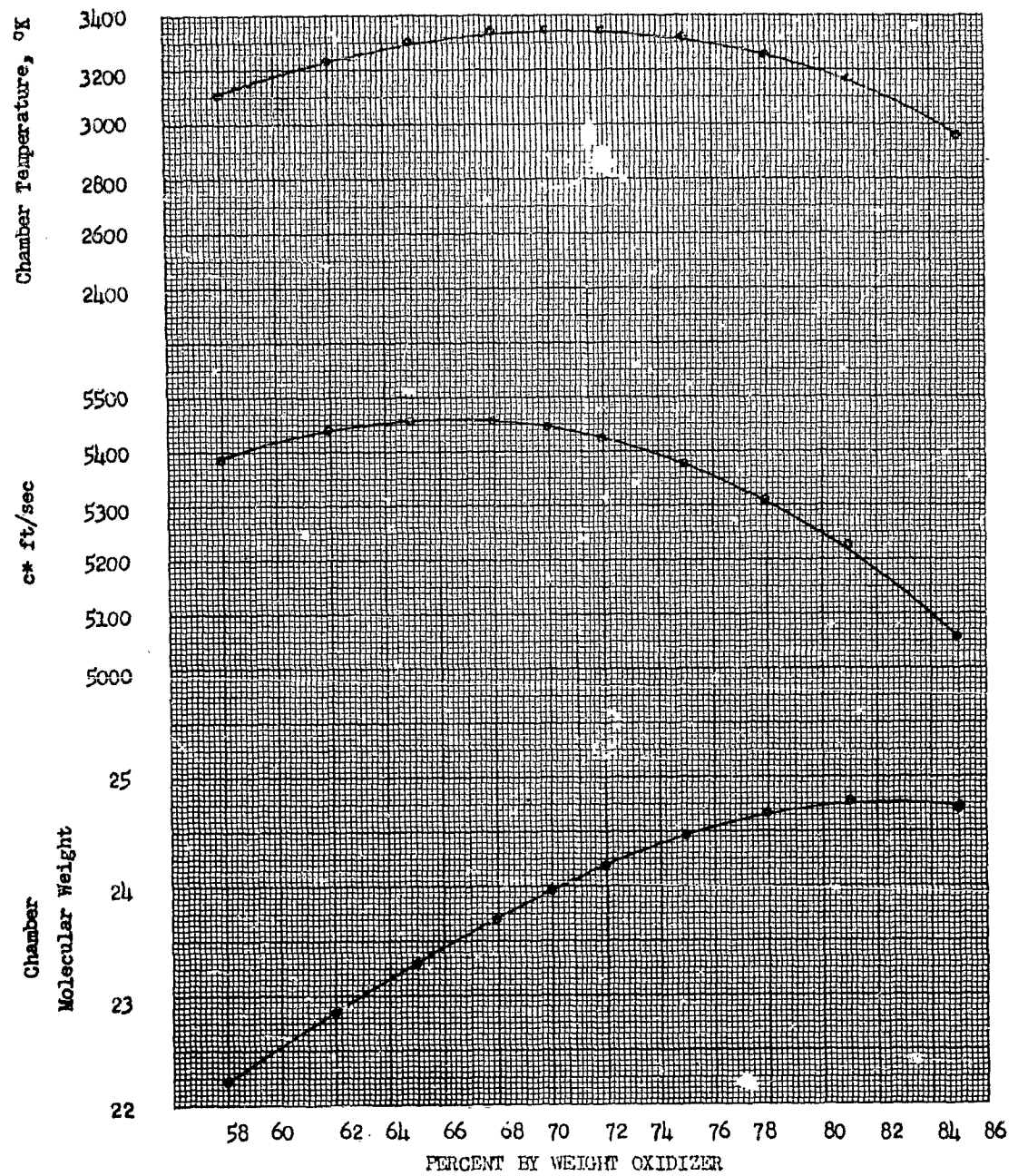
□ $p_c/p_a = 68$

○ $p_c/p_a = 500$

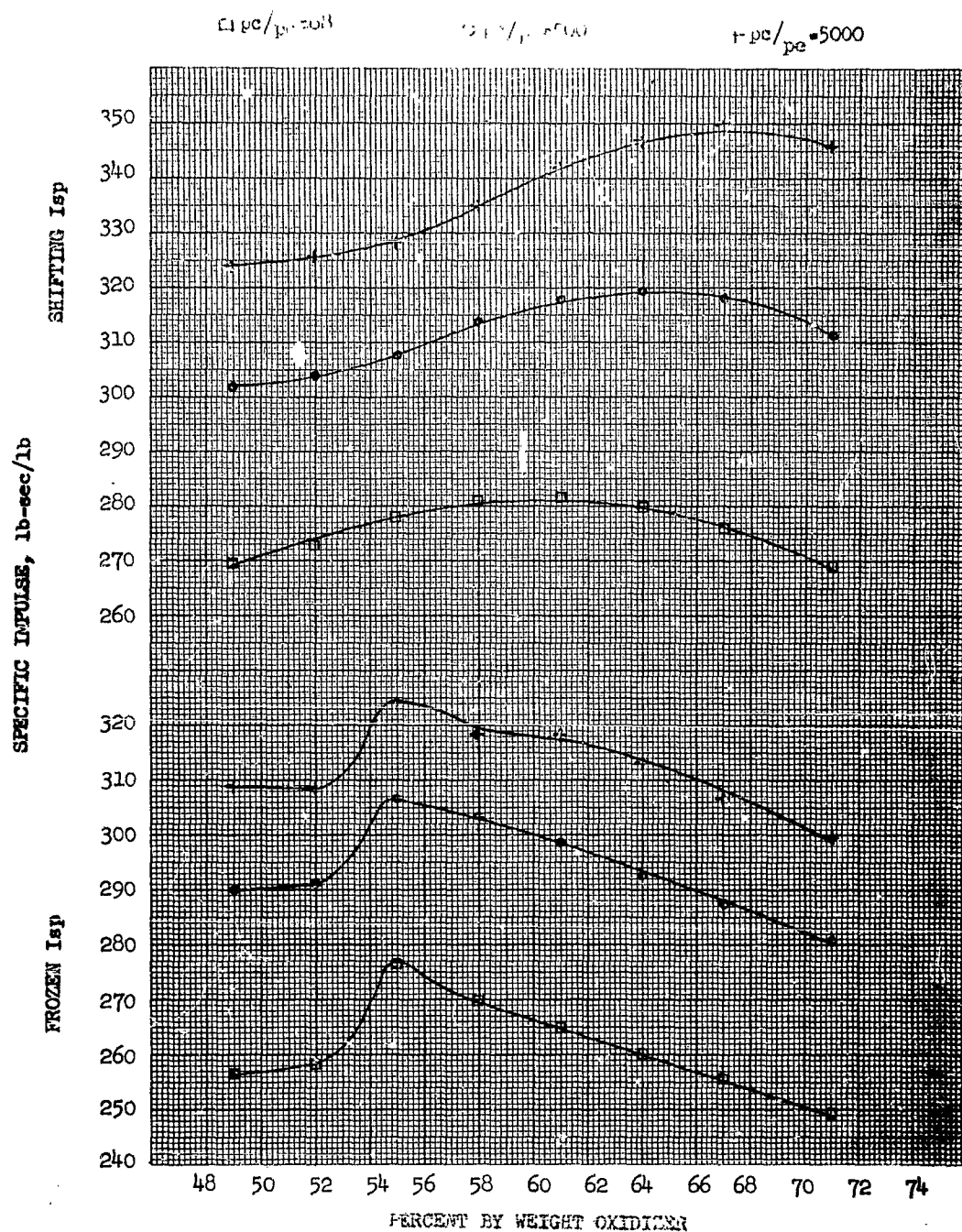
+ $p_c/p_a = 5000$



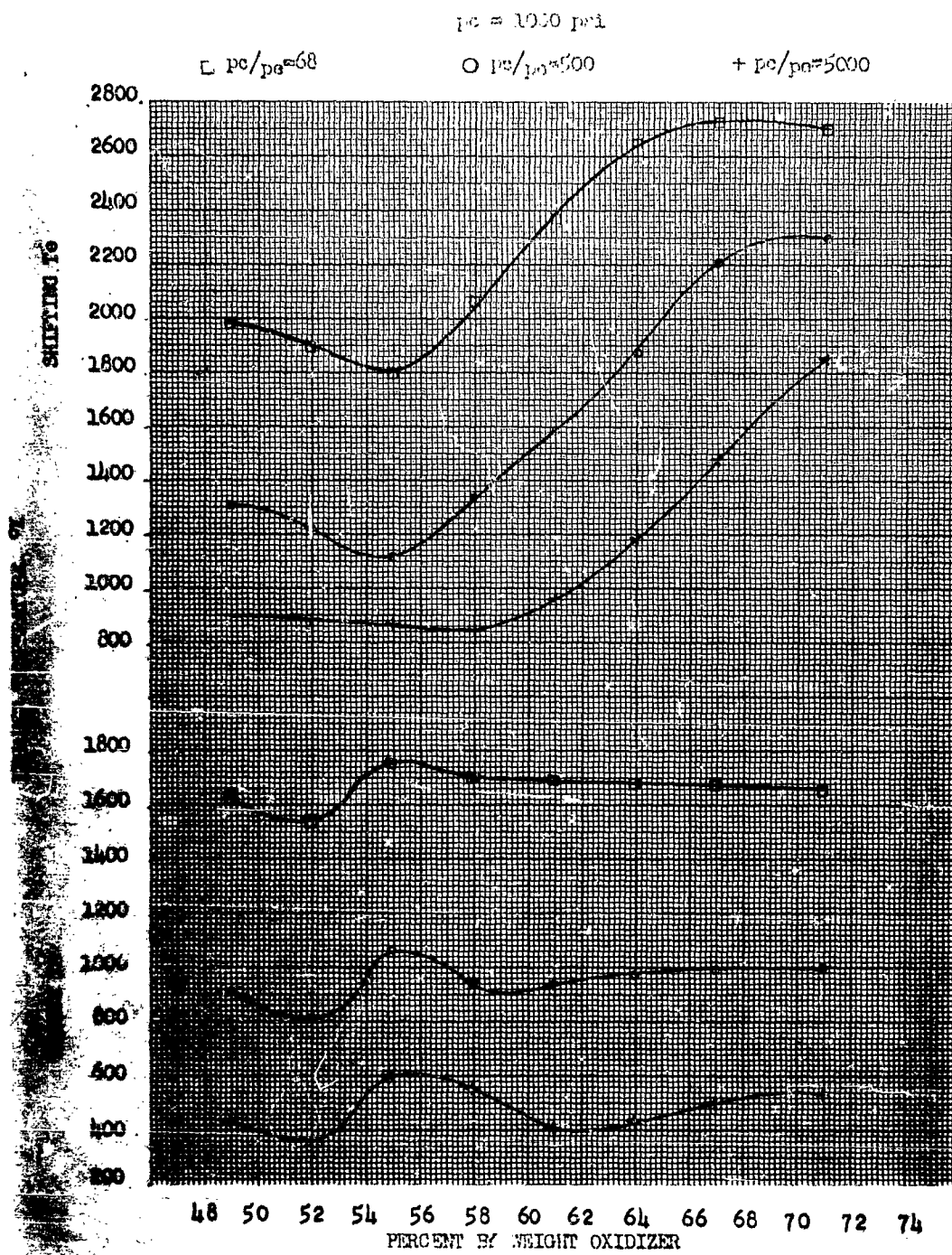
DICIANOACETYLENE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 132



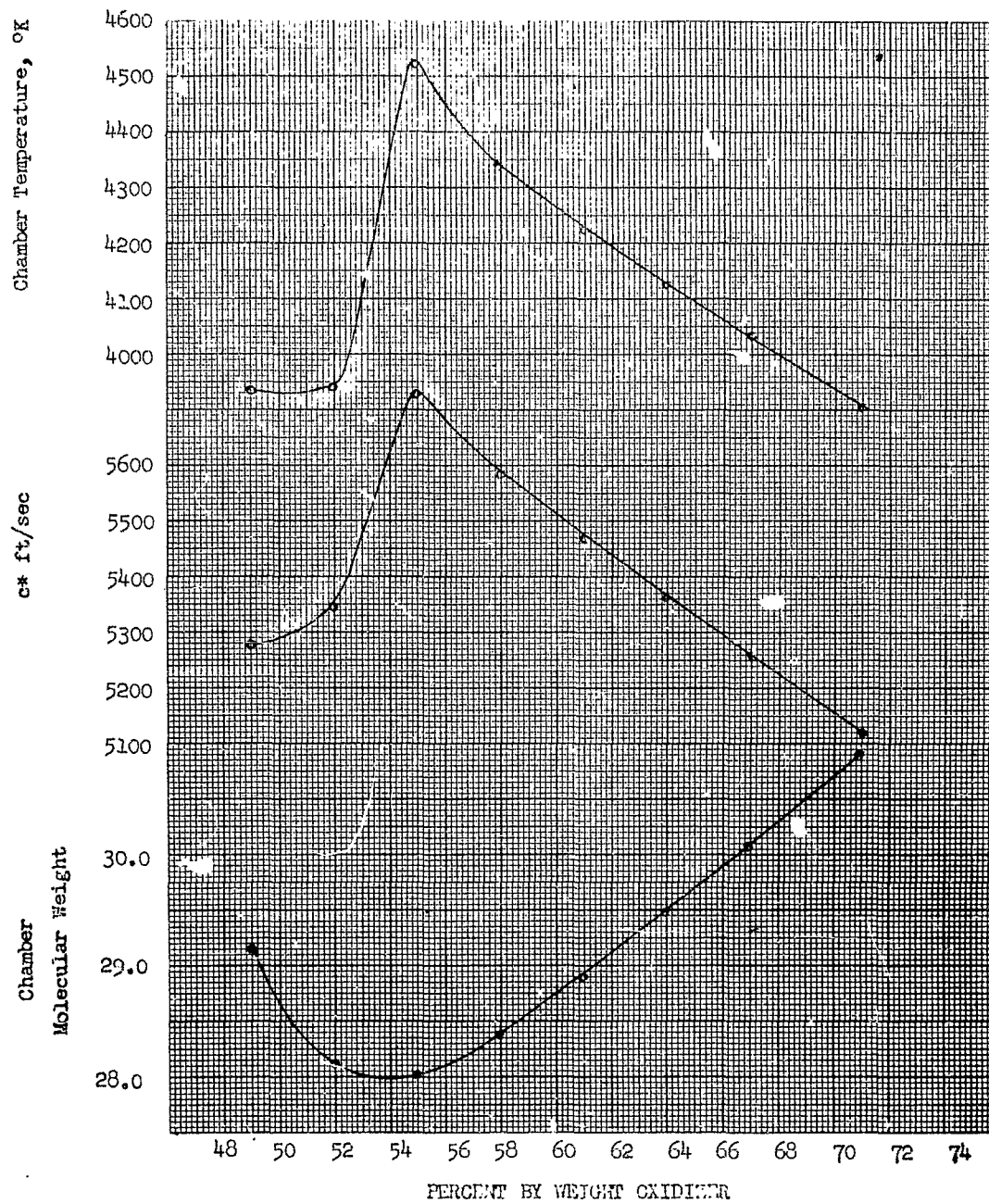
DICYANACETYLENE-NITROGEN TETROXIDE FORMULATIONS CURVES FIGURE 1.33
 (continued)



D'NIANOACETYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 134

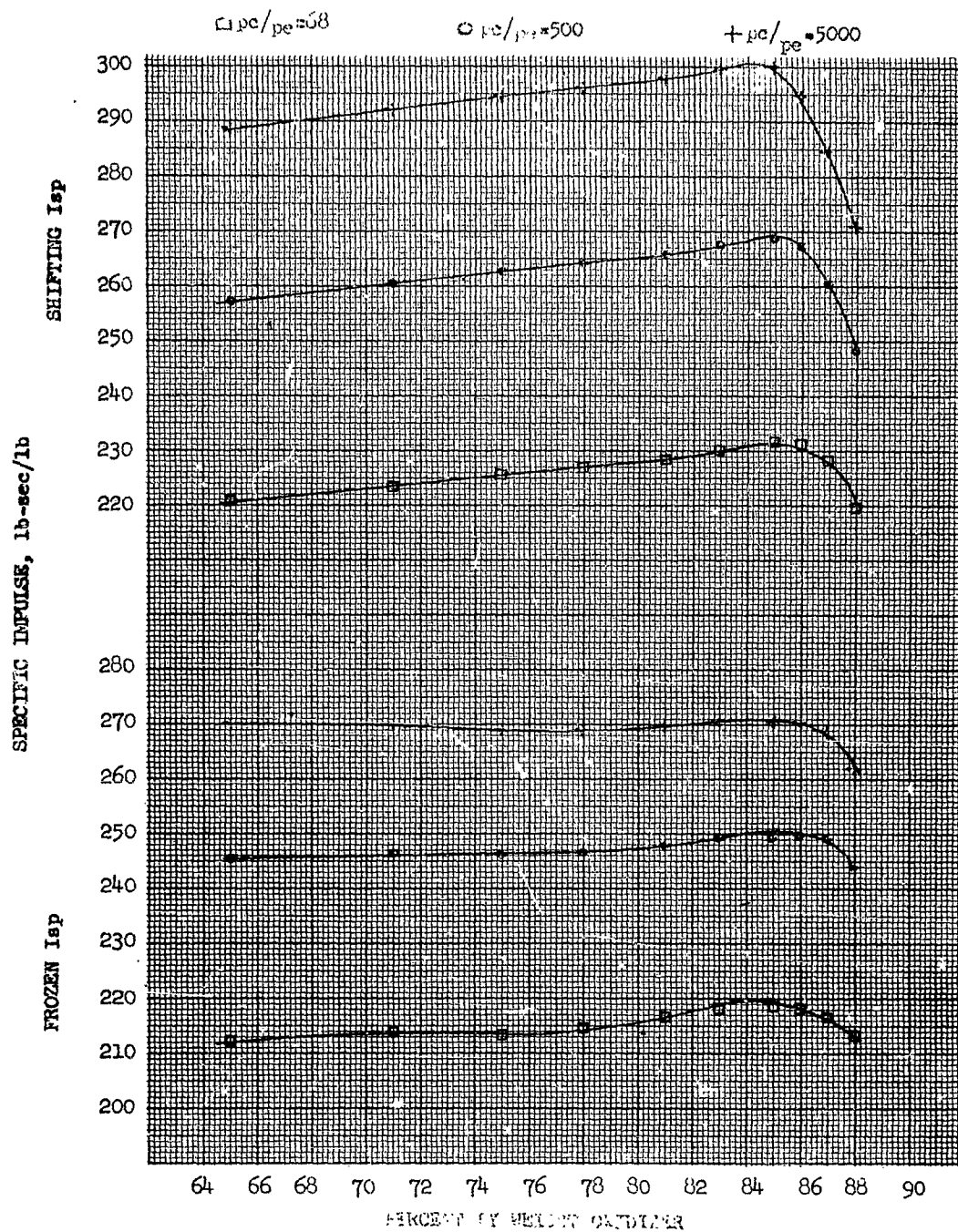


DICYANACETYLENE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 135

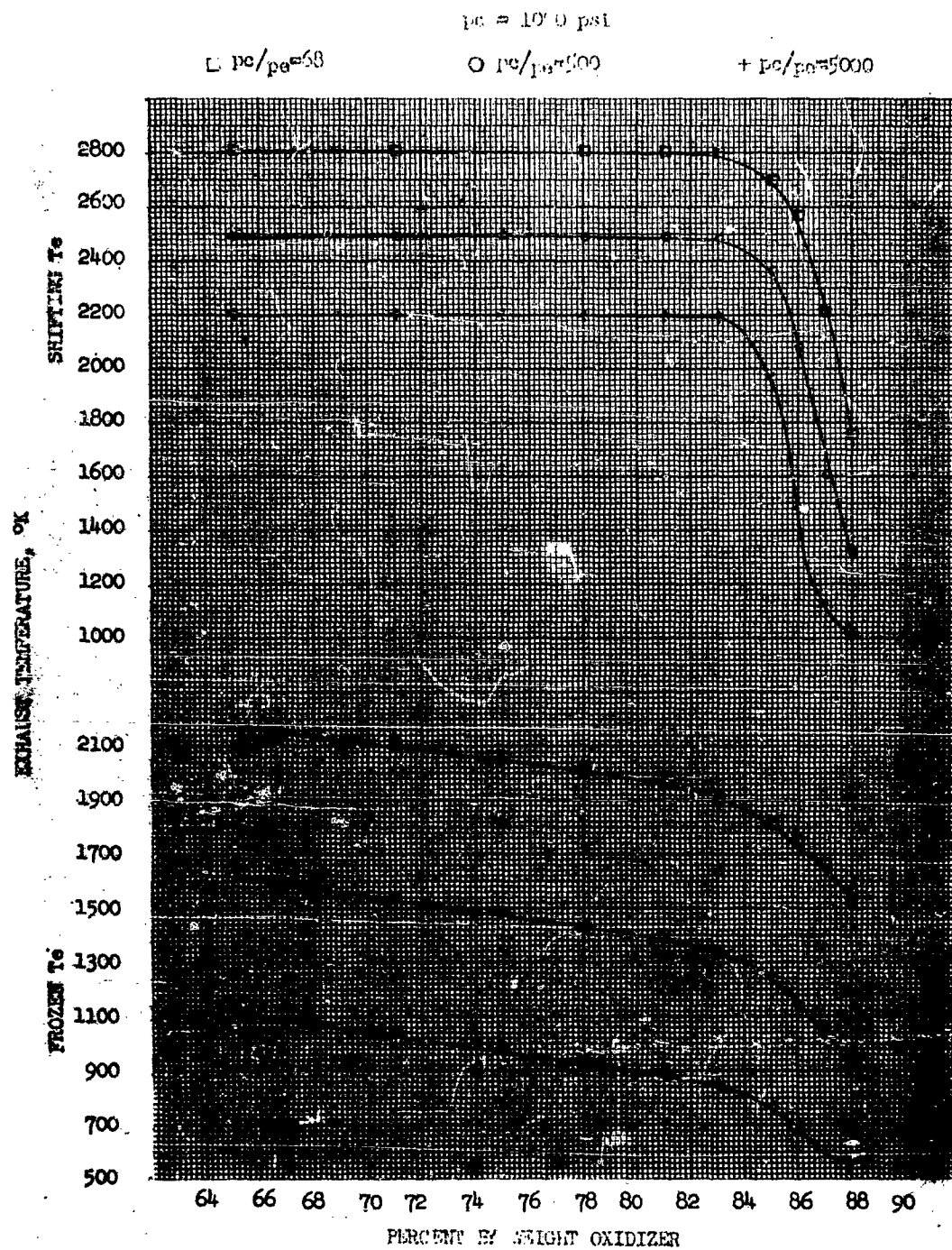


DICYANOACETYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 136

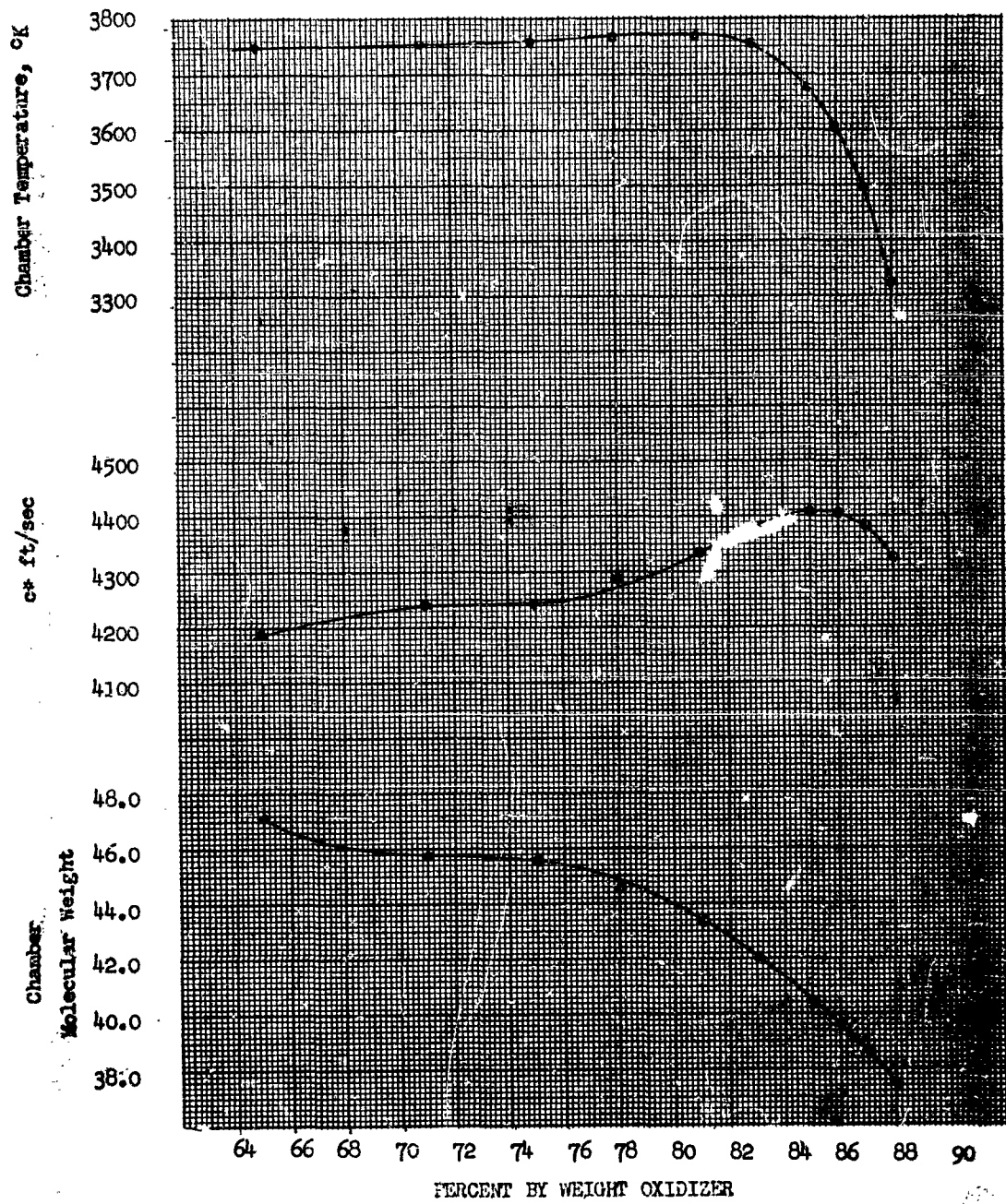
pc = 1000 psi



DICYANOACETYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 137

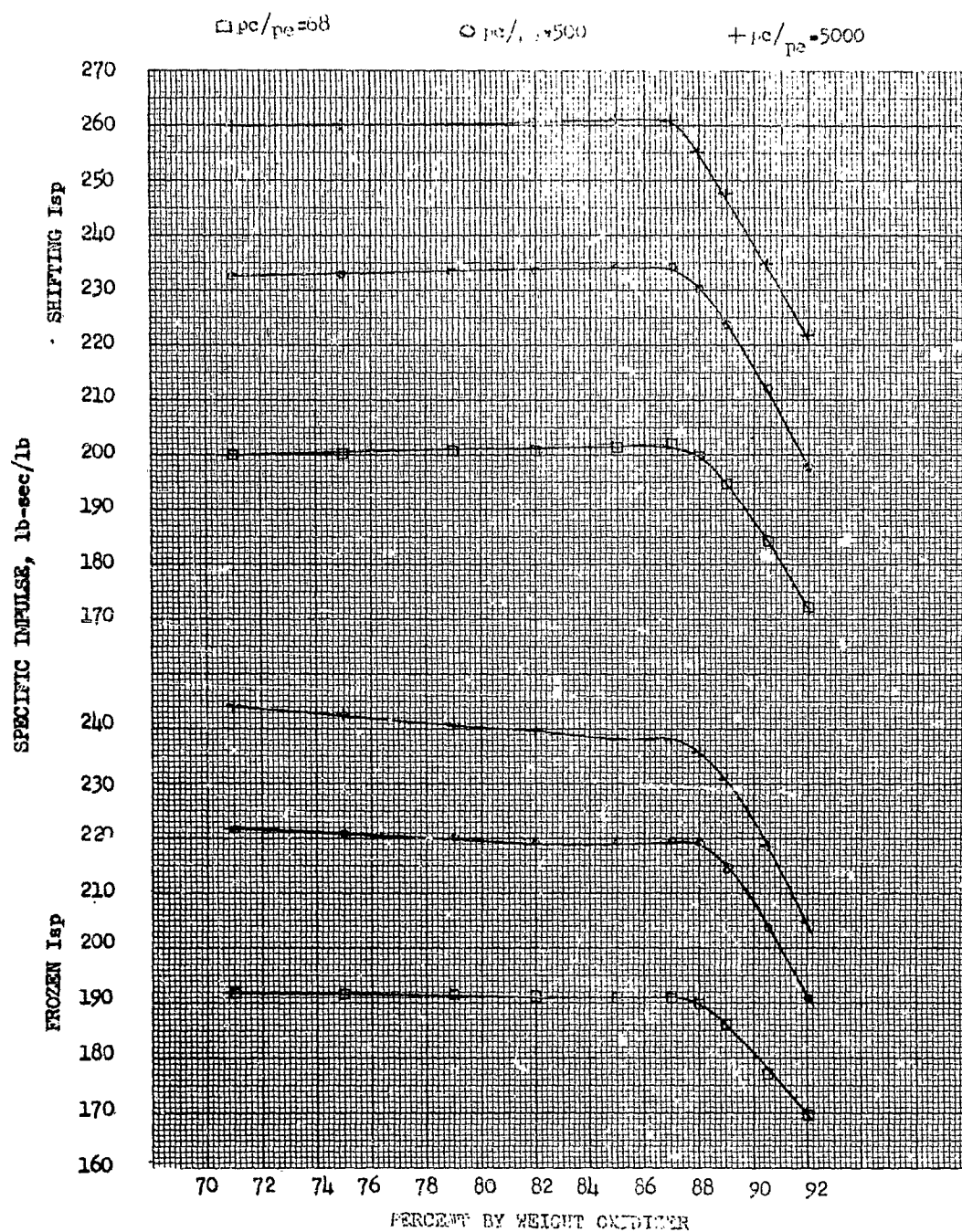


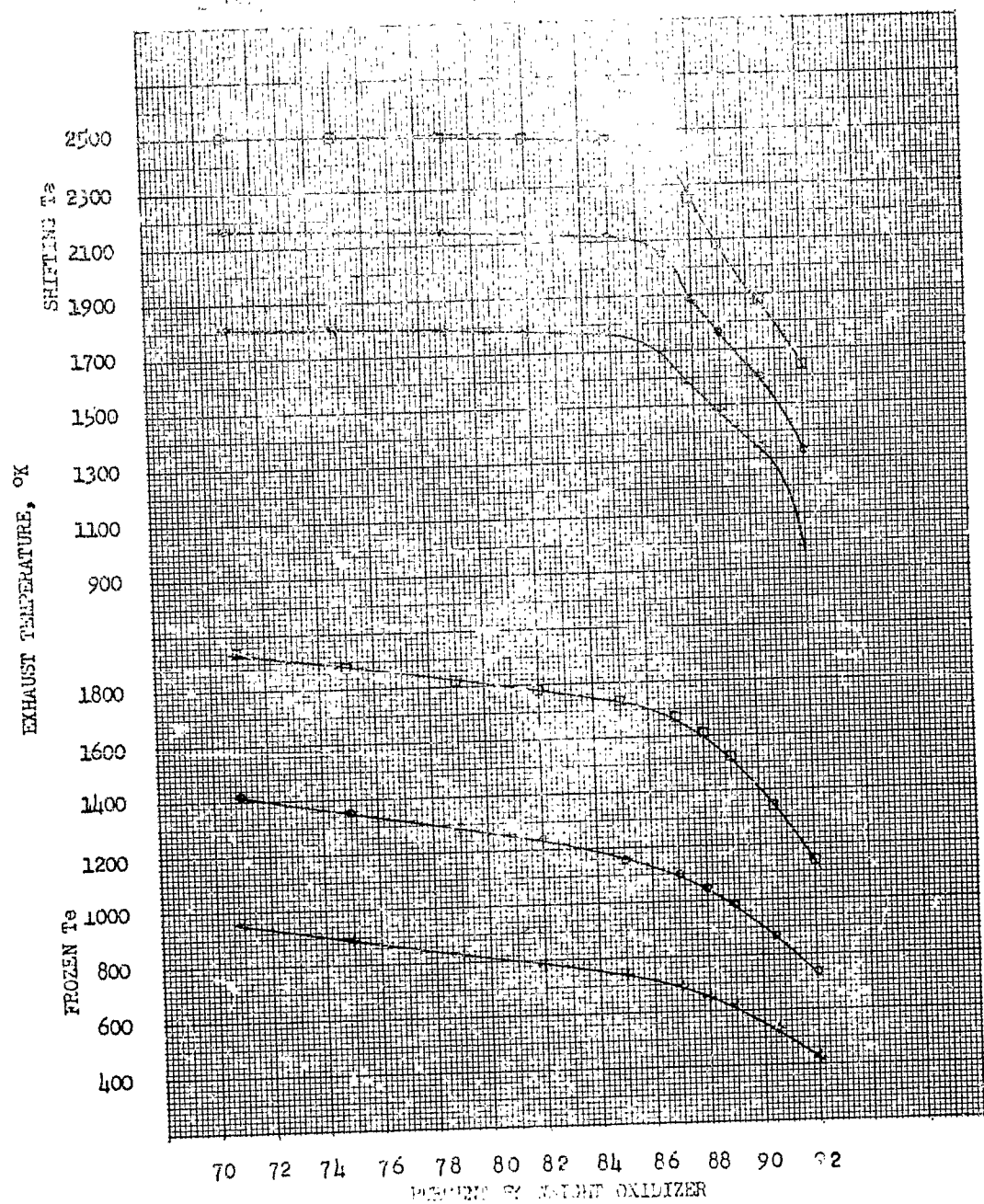
DICYANOACETYLENE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 138



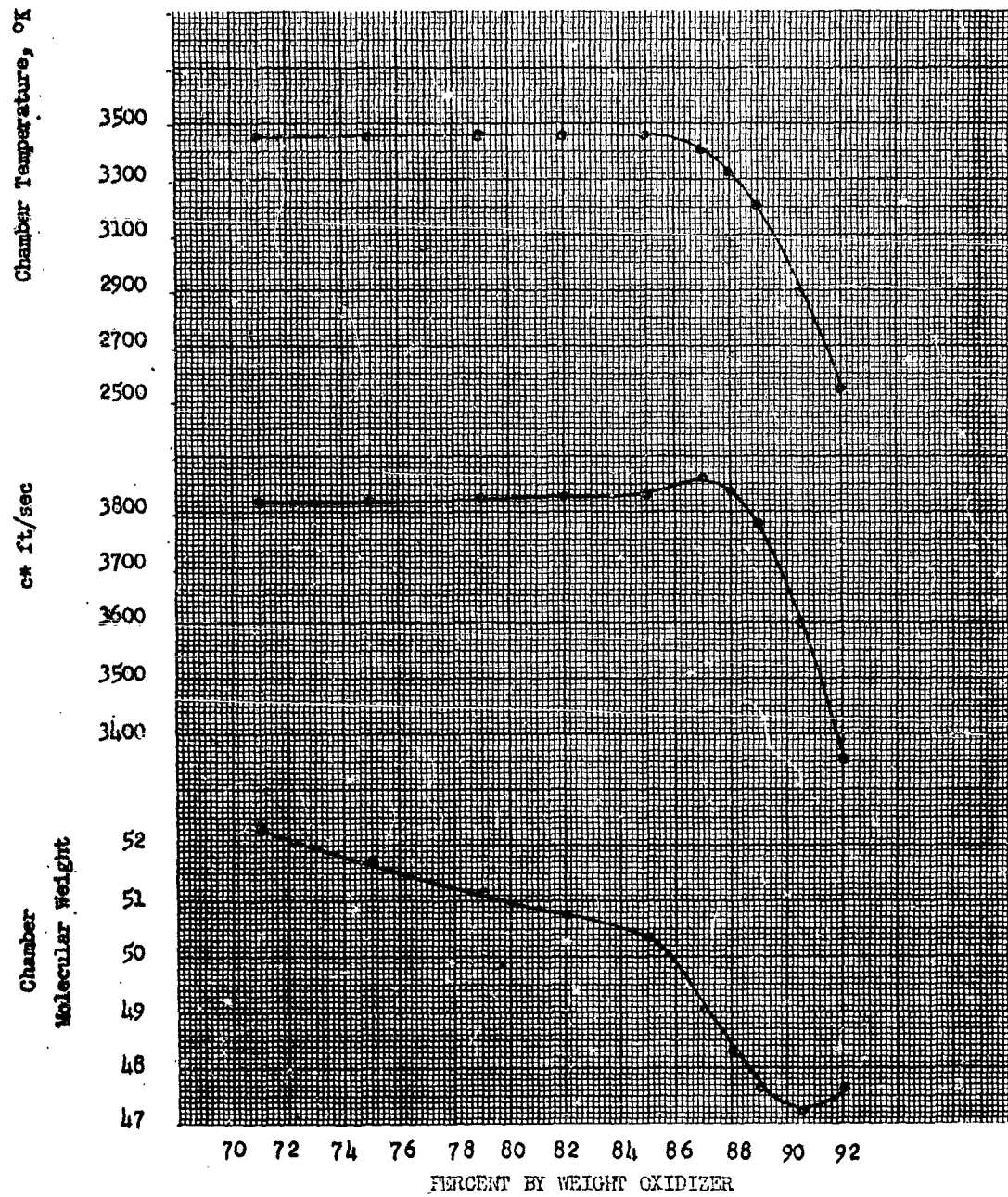
DICYANOACETYLENE - CHLORINE TRIFLUORIDE PROPELLANT MIXTURES FIGURE 139

(continued)

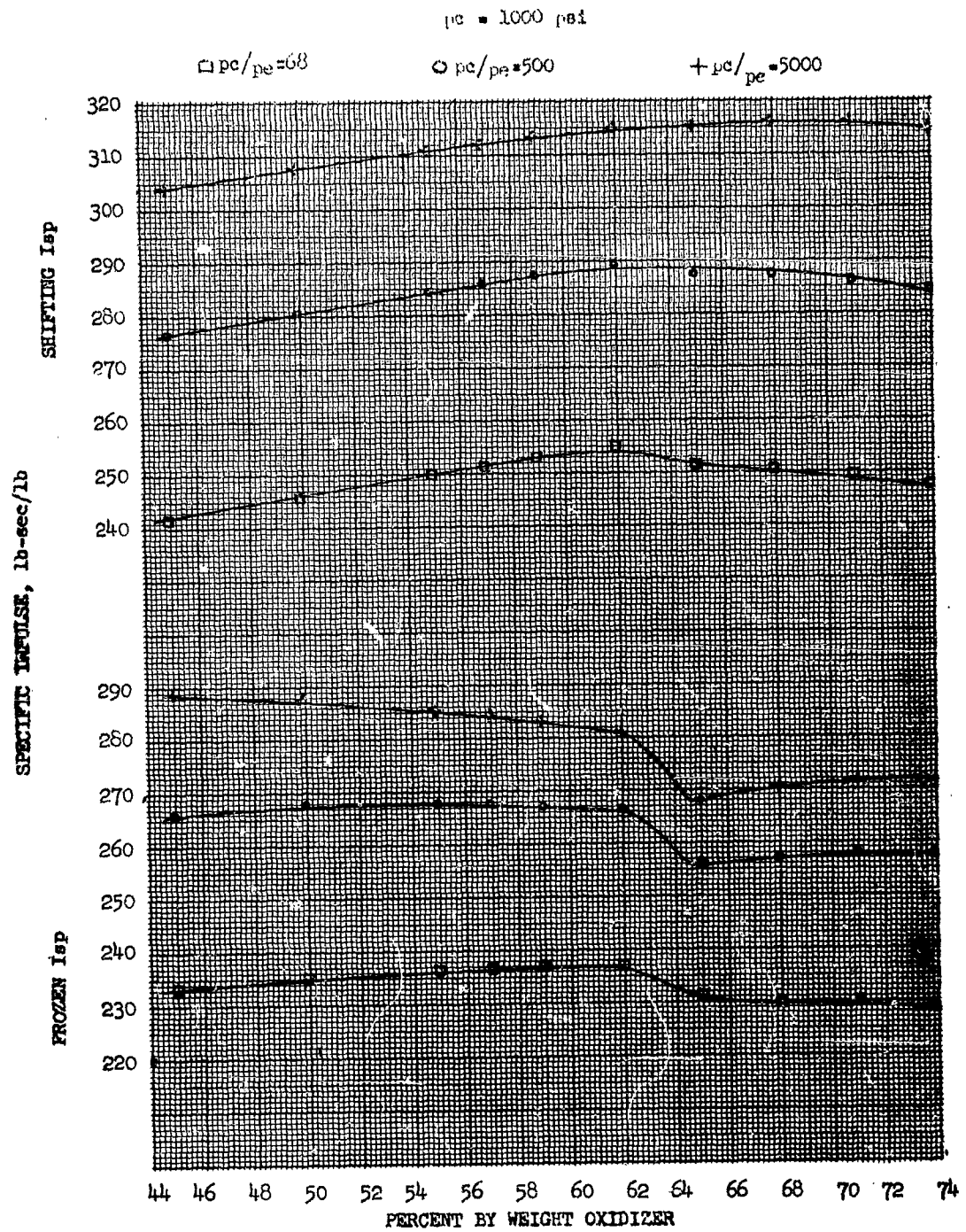


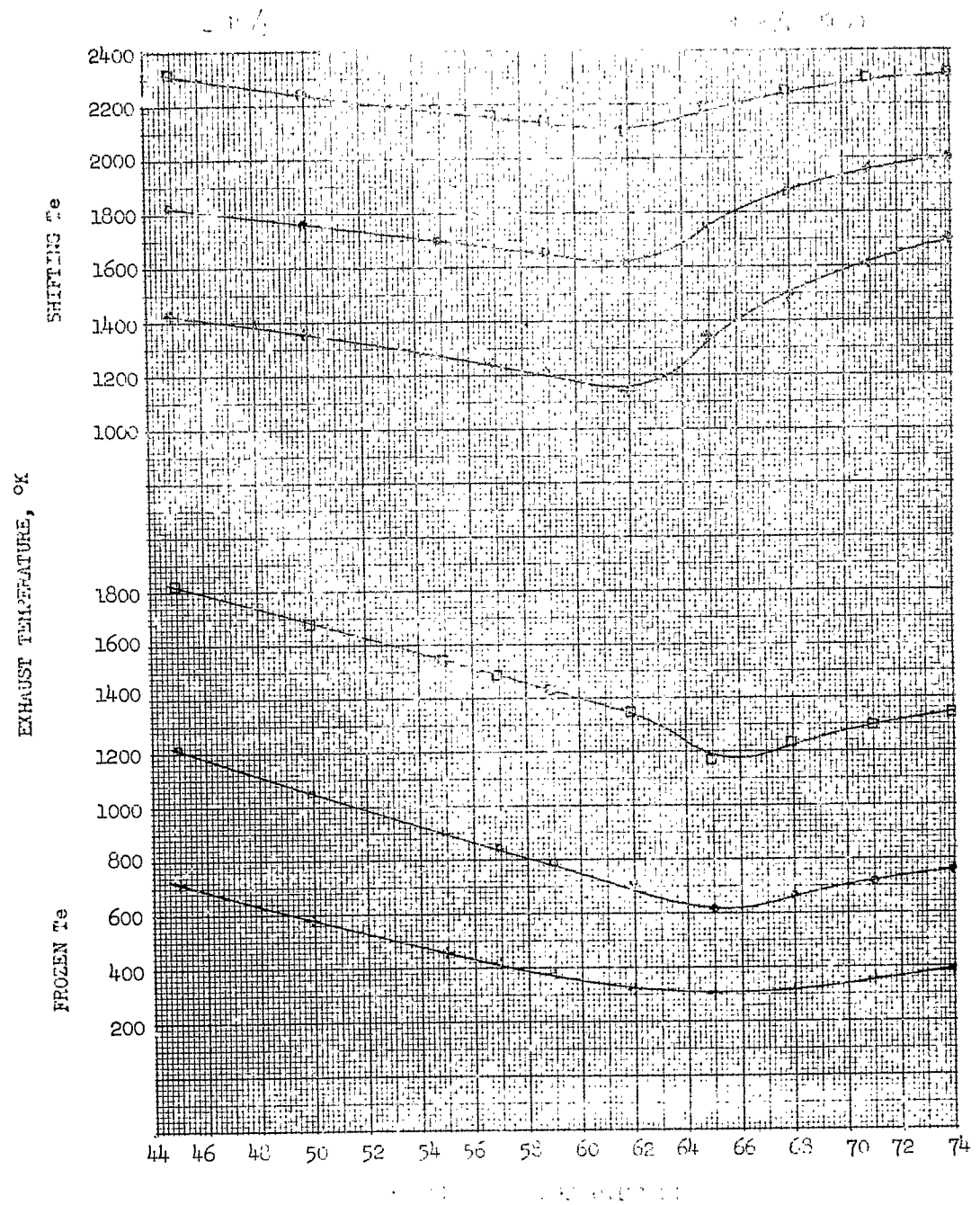


DICYANOACETYLENE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 141

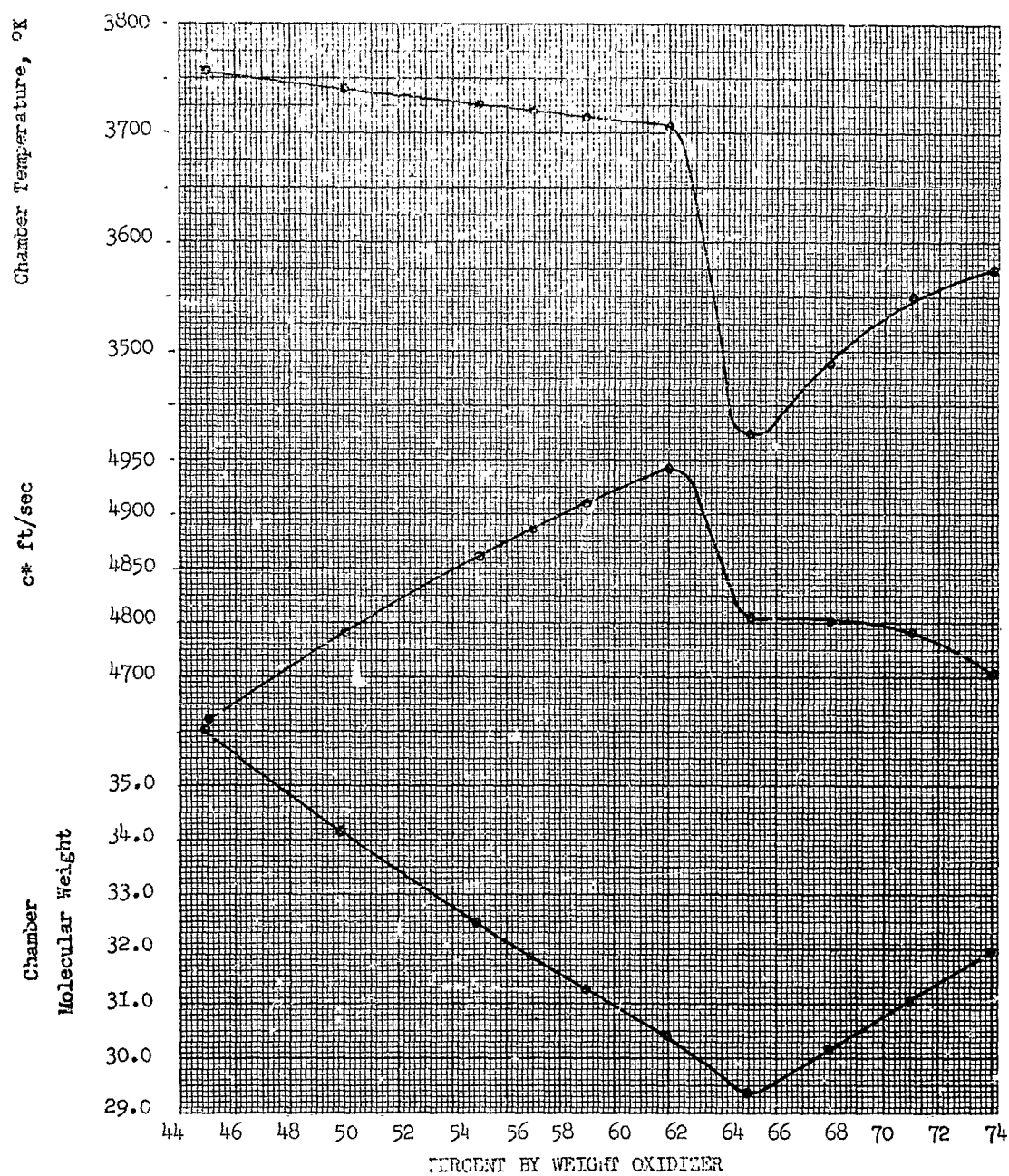


DICYANOACETYLENE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 142





DICYANACETYLENE - SECONDARY PROXIDE PERFORMANCE CURVES FIGURE 144



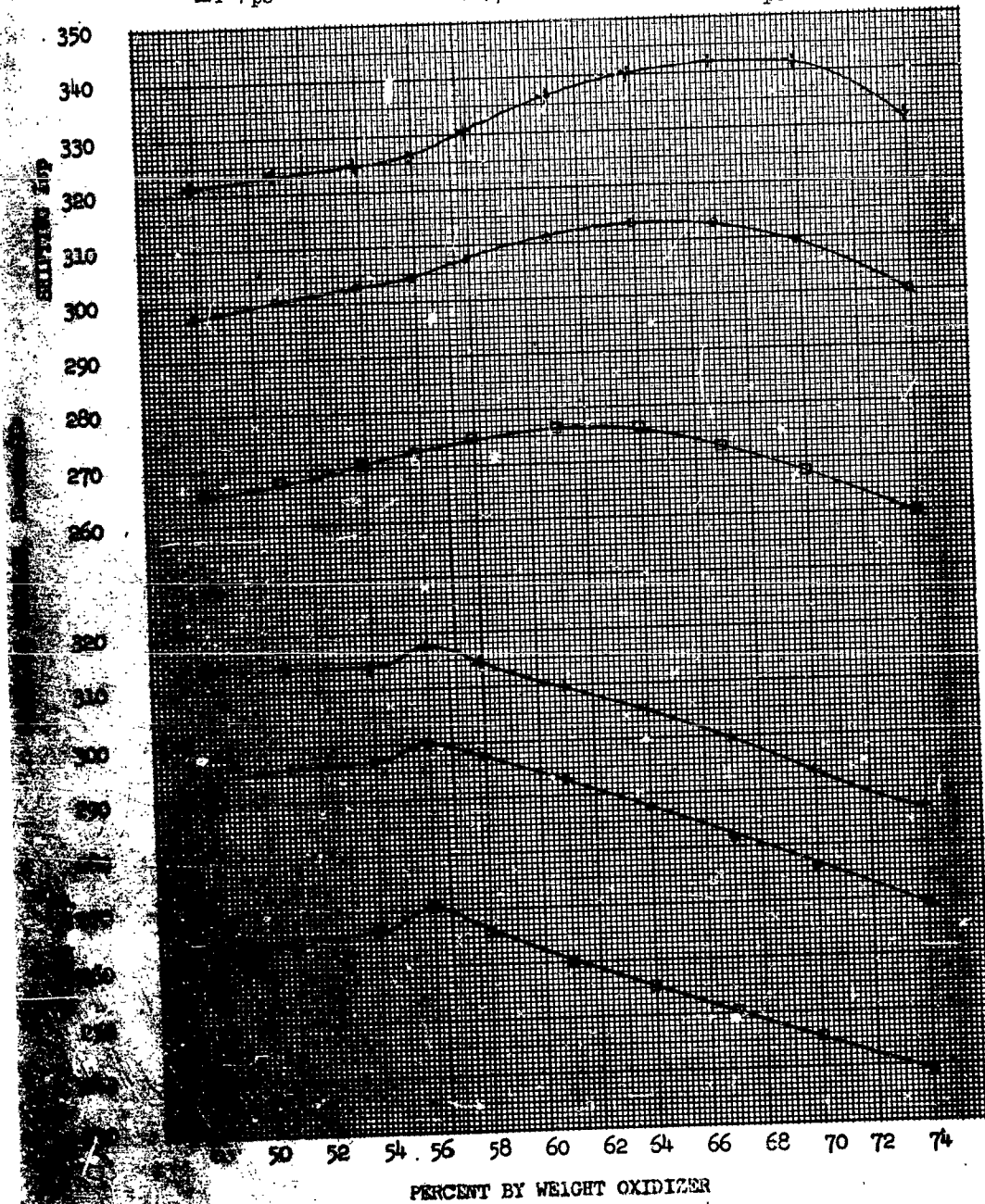
DICYANOACETYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 115

$p_c = 1000 \text{ psi}$

$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$



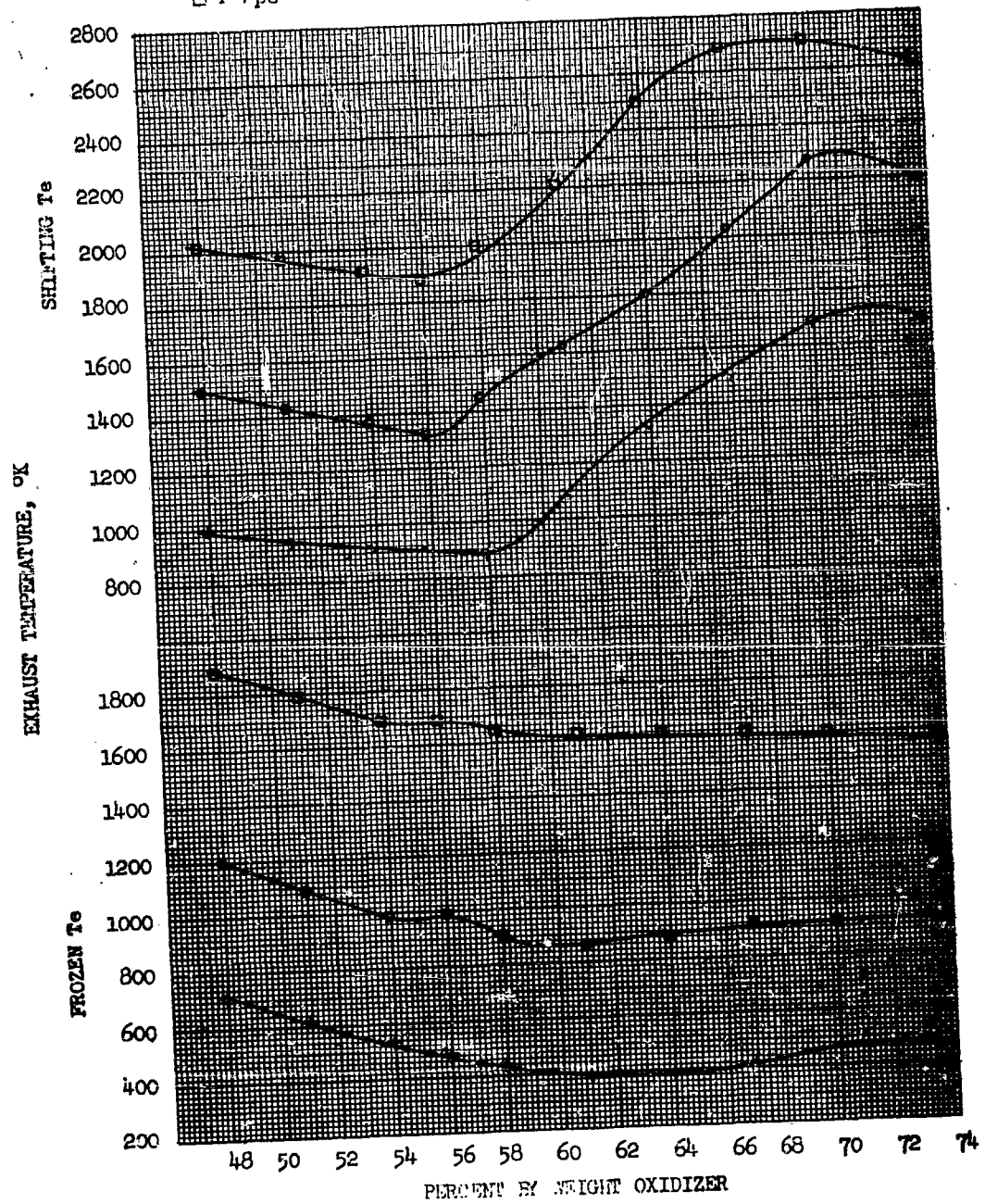
DICYANOACETYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 146

$p_c = 1000 \text{ psi}$

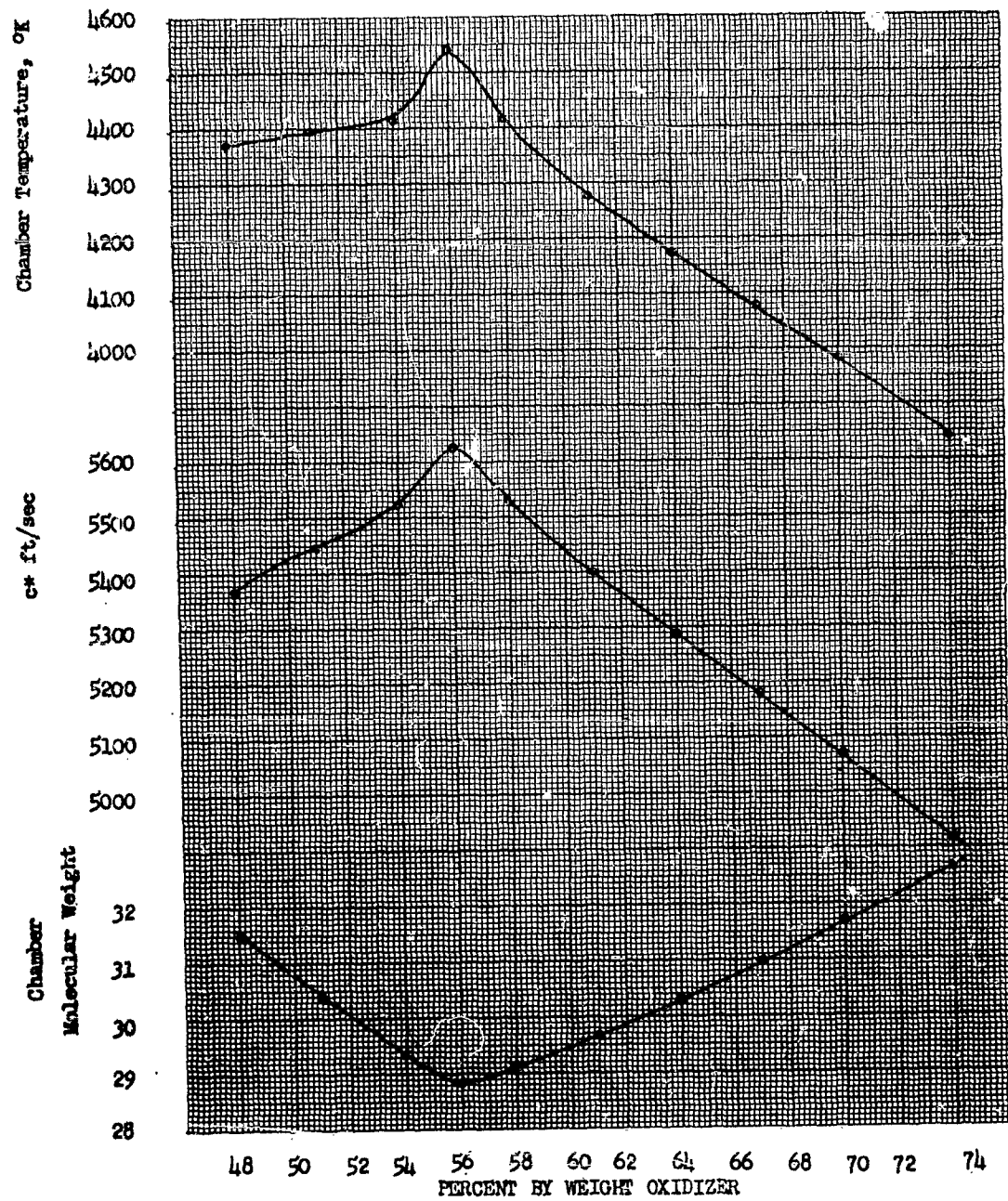
\square $p_c/p_o = 68$

\circ $p_c/p_o = 500$

$+ p_c/p_o = 5000$



DICYANOACETYLENE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 117



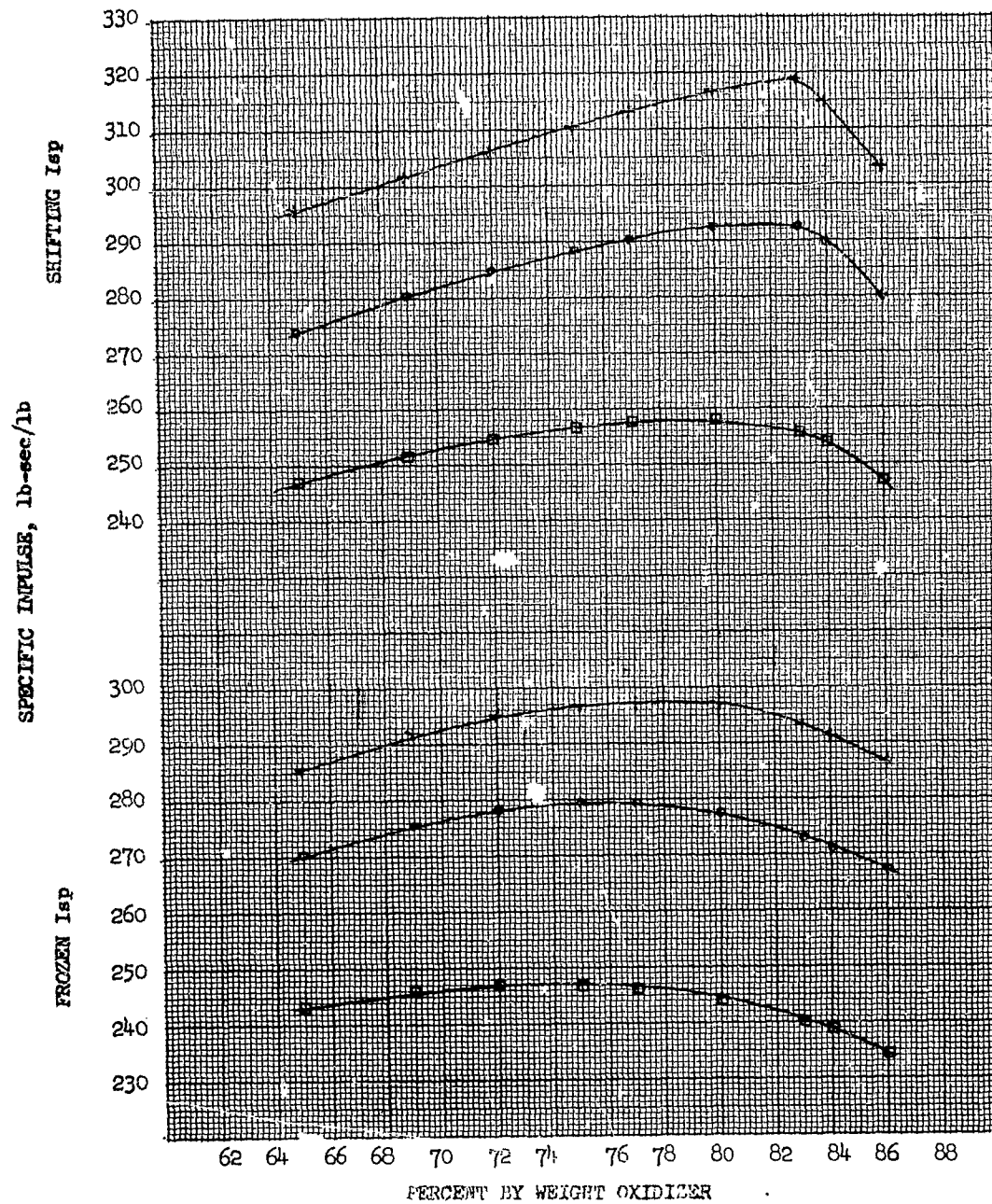
DICYANOACETYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 148

pc = 1500 psi

□ pc/pe = 200

○ pc/pe = 500

+ pc/pe = 5000



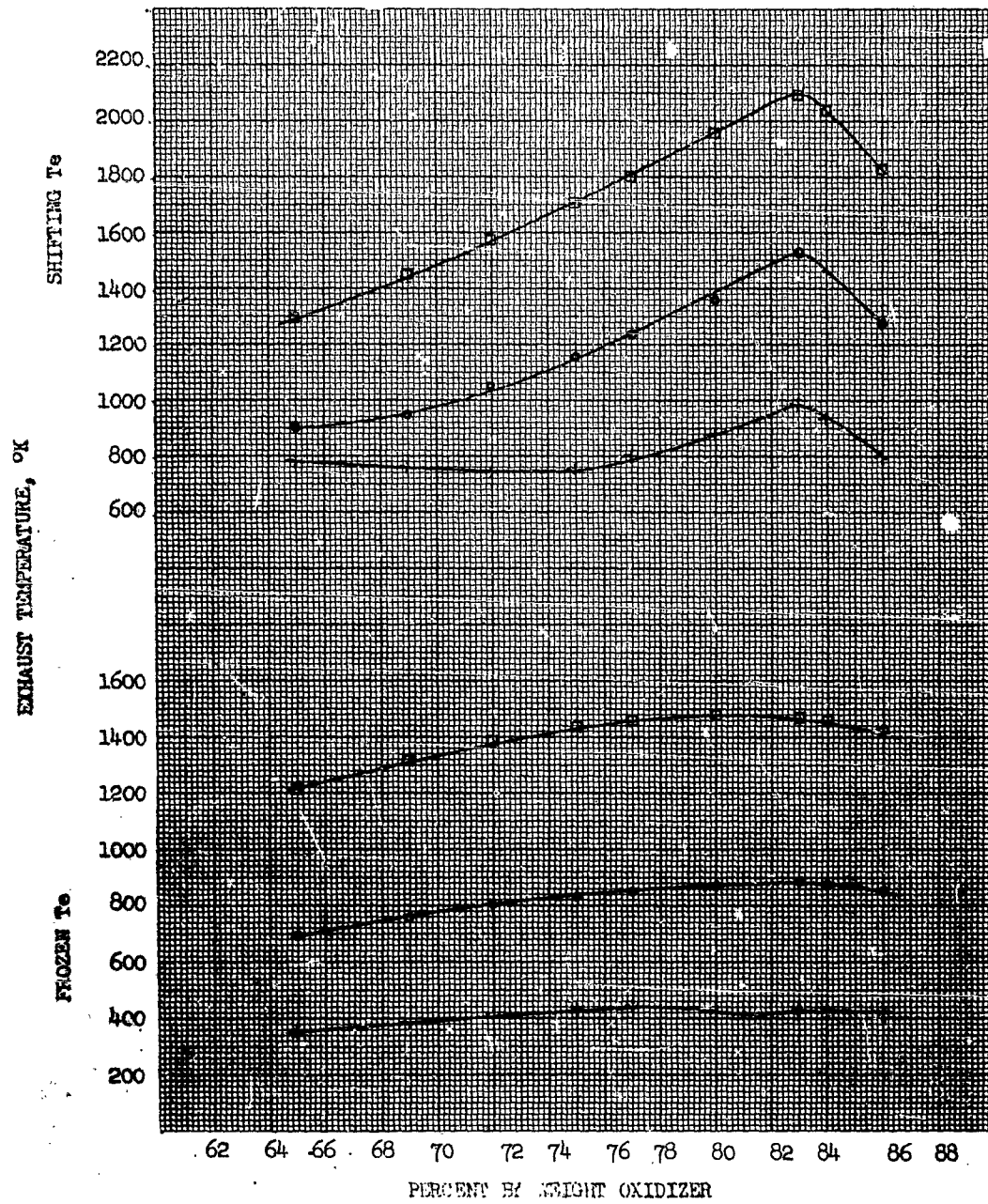
DICYANOACETYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 1-9

$p_c = 1000 \text{ psi}$

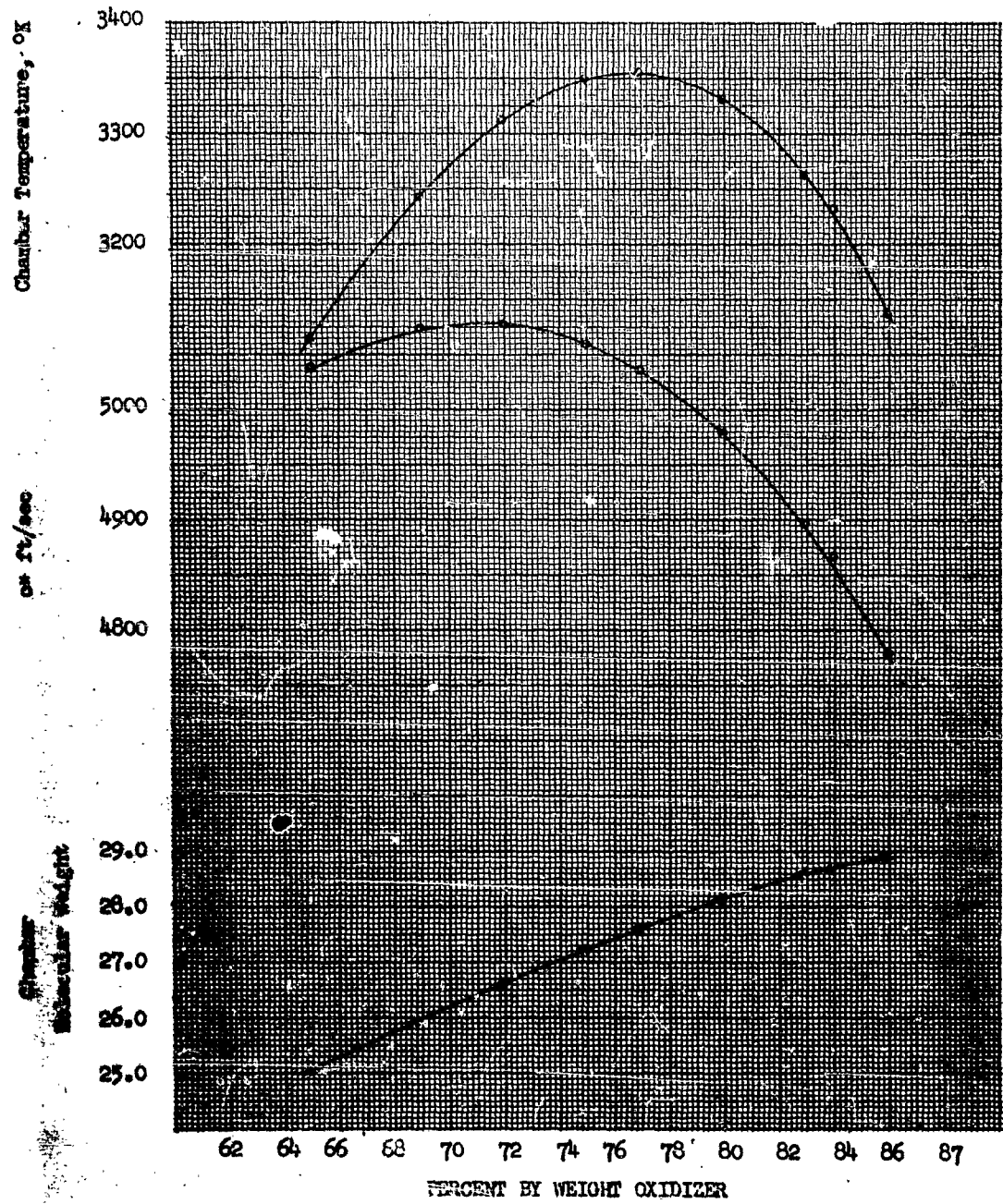
$\square p_c/p_a = 68$

$\circ p_c/p_a = 500$

$+ p_c/p_a = 5000$



DICYANOACETYLENE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 110



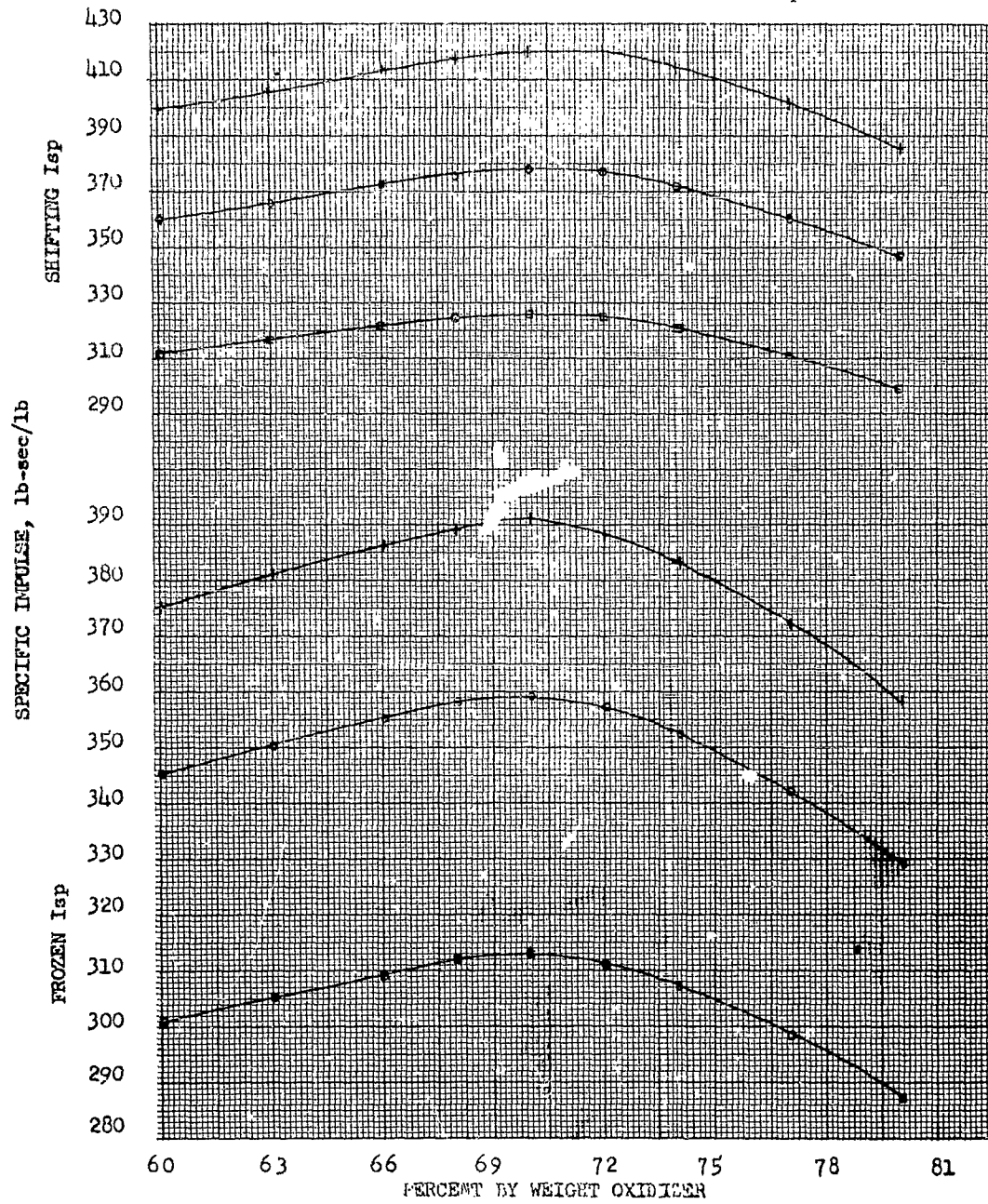
PENTAFORMANE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 151

$\alpha = 0.00131$

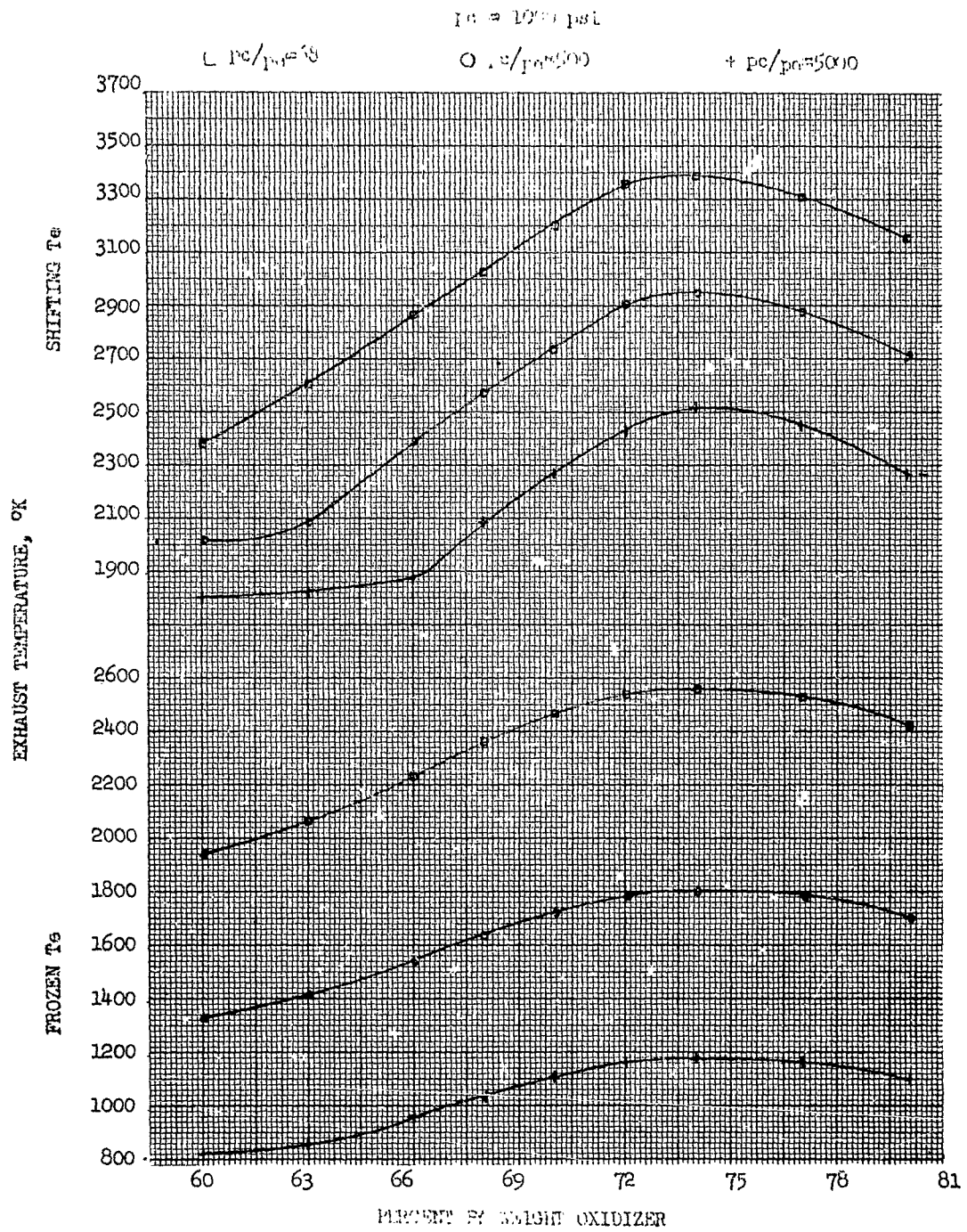
\square $p_c/p_e = 203$

\circ $p_c/p_e = 500$

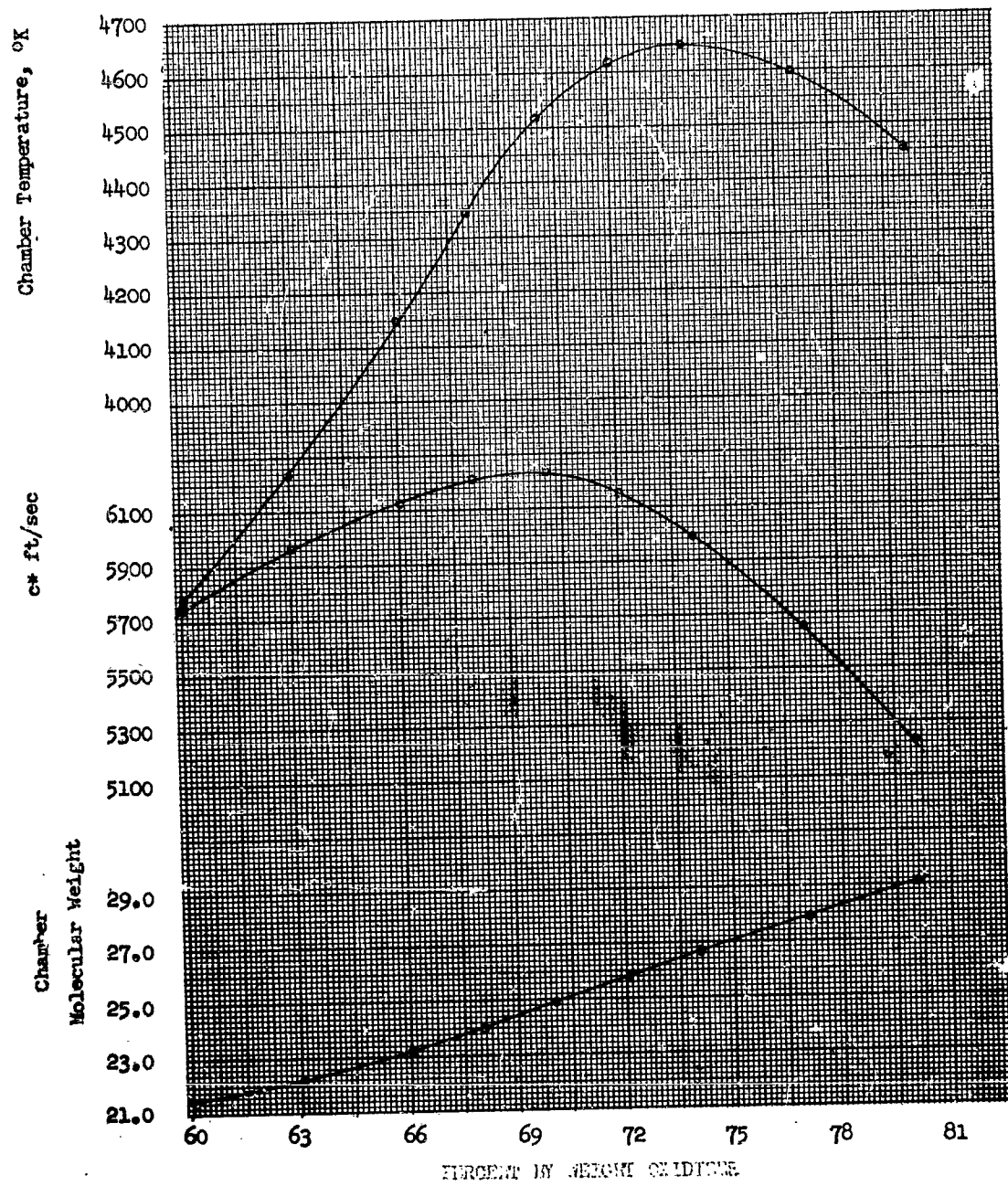
$+$ $p_c/p_e = 5000$



PENTABORANE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 152



PENTABORANE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 153



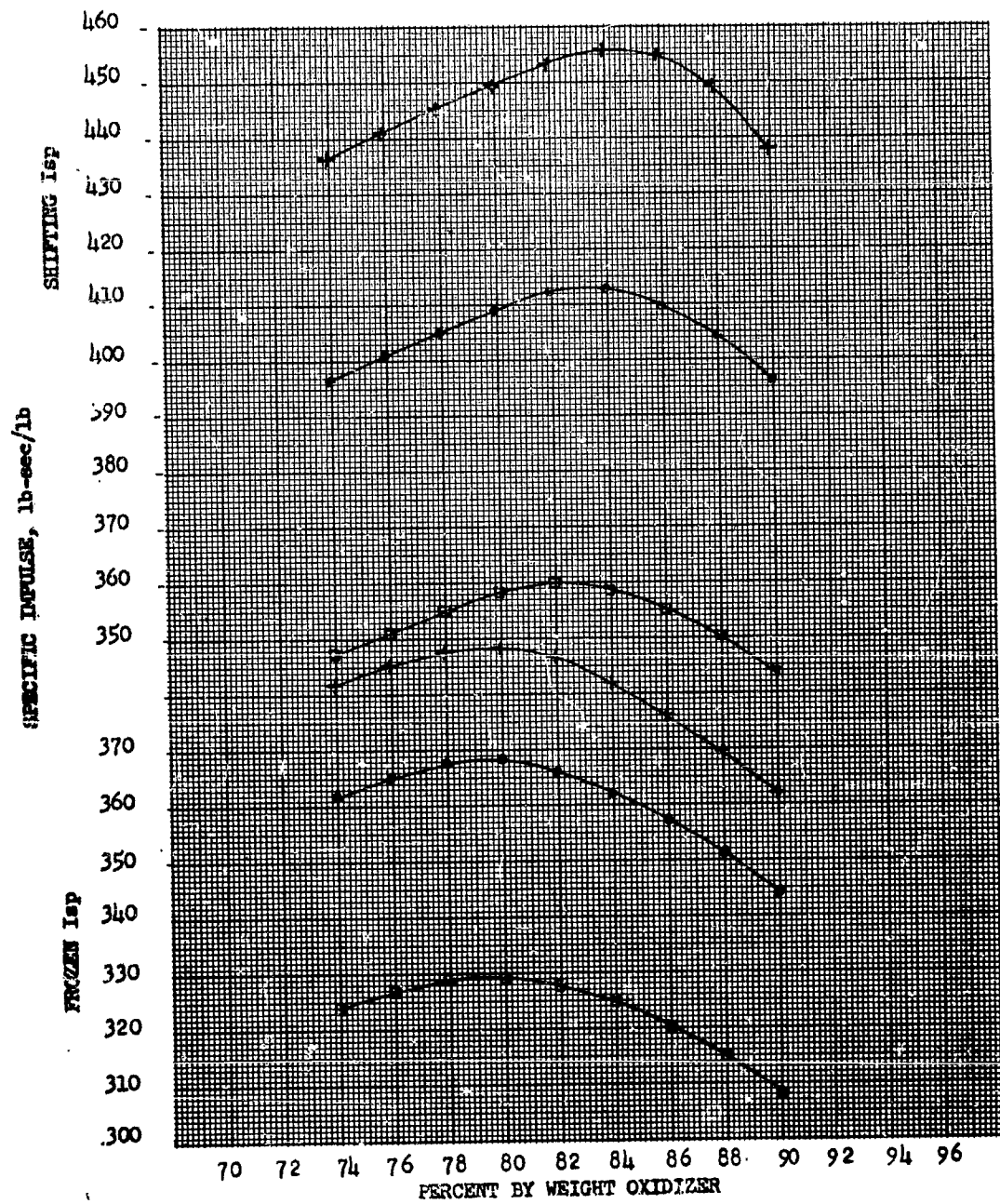
PENTABORANE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 154

pc = 1000 psi

□ pc/pe = 68

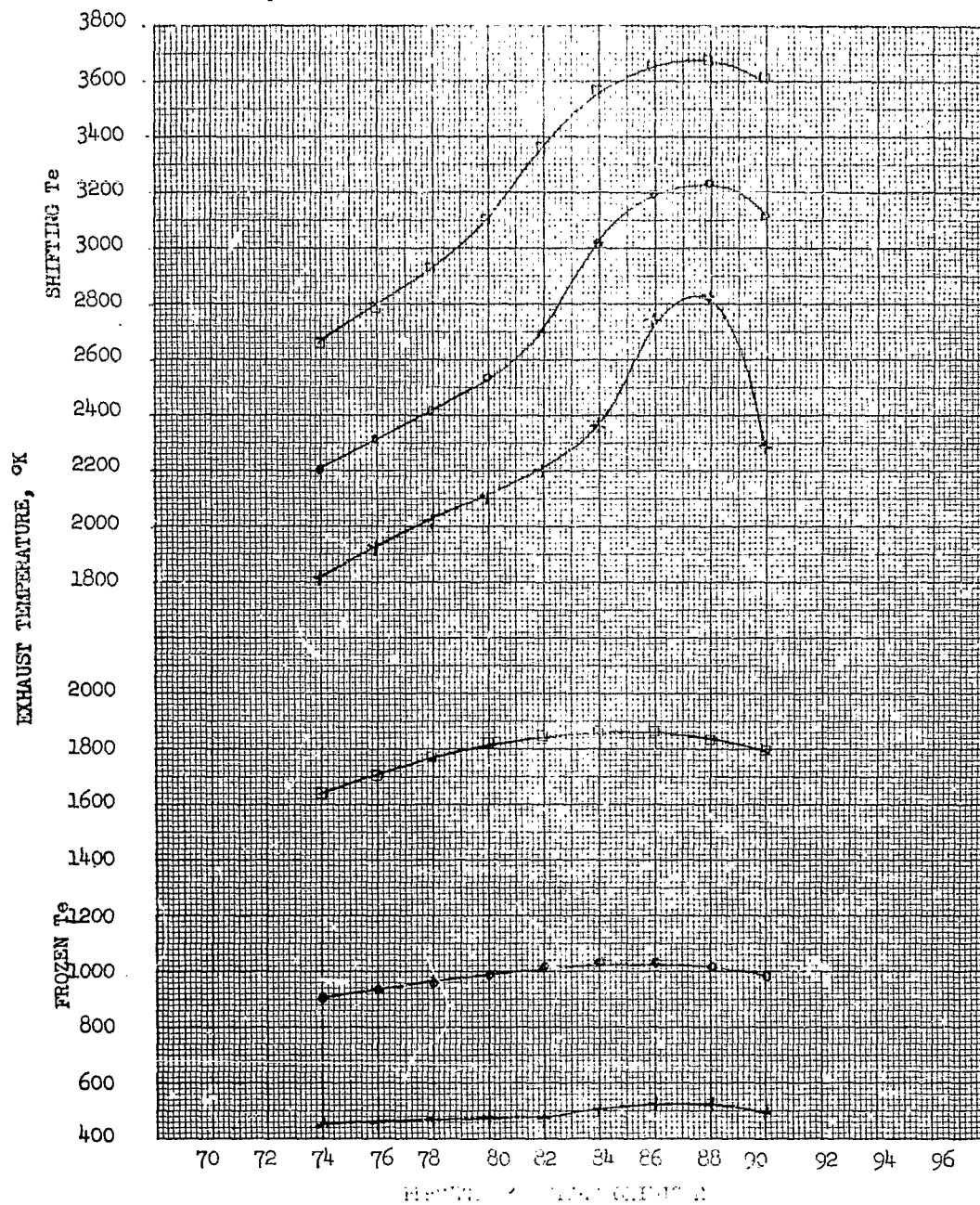
○ pc/pe = 500

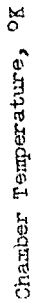
+ pc/pe = 5000



1 PC/1.2-12

1.0/1.0000





c# ft/sec

Chariber	Molecular Weight
1	100
2	200
3	300
4	400
5	500
6	600
7	700
8	800
9	900
10	1000
11	1100
12	1200
13	1300
14	1400
15	1500
16	1600
17	1700
18	1800
19	1900
20	2000
21	2100
22	2200
23	2300
24	2400
25	2500
26	2600
27	2700
28	2800
29	2900
30	3000
31	3100
32	3200
33	3300
34	3400
35	3500
36	3600
37	3700
38	3800
39	3900
40	4000
41	4100
42	4200
43	4300
44	4400
45	4500
46	4600
47	4700
48	4800
49	4900
50	5000
51	5100
52	5200
53	5300
54	5400
55	5500
56	5600
57	5700
58	5800
59	5900
60	6000
61	6100
62	6200
63	6300
64	6400
65	6500
66	6600
67	6700
68	6800
69	6900
70	7000
71	7100
72	7200
73	7300
74	7400
75	7500
76	7600
77	7700
78	7800
79	7900
80	8000
81	8100
82	8200
83	8300
84	8400
85	8500
86	8600
87	8700
88	8800
89	8900
90	9000
91	9100
92	9200
93	9300
94	9400
95	9500
96	9600
97	9700
98	9800
99	9900
100	10000

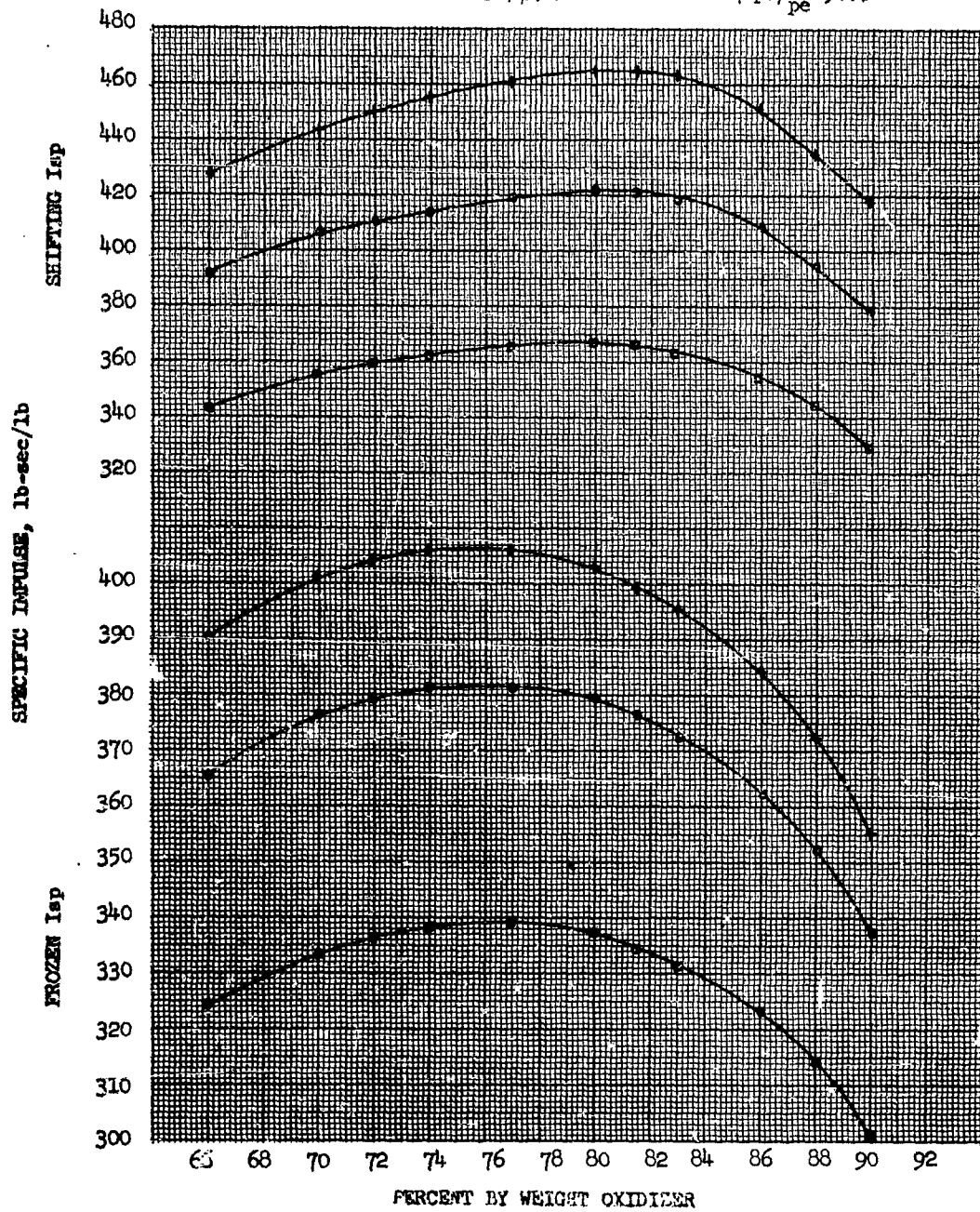
PENTABORANE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 157

$p_c = 1000 \text{ psi}$

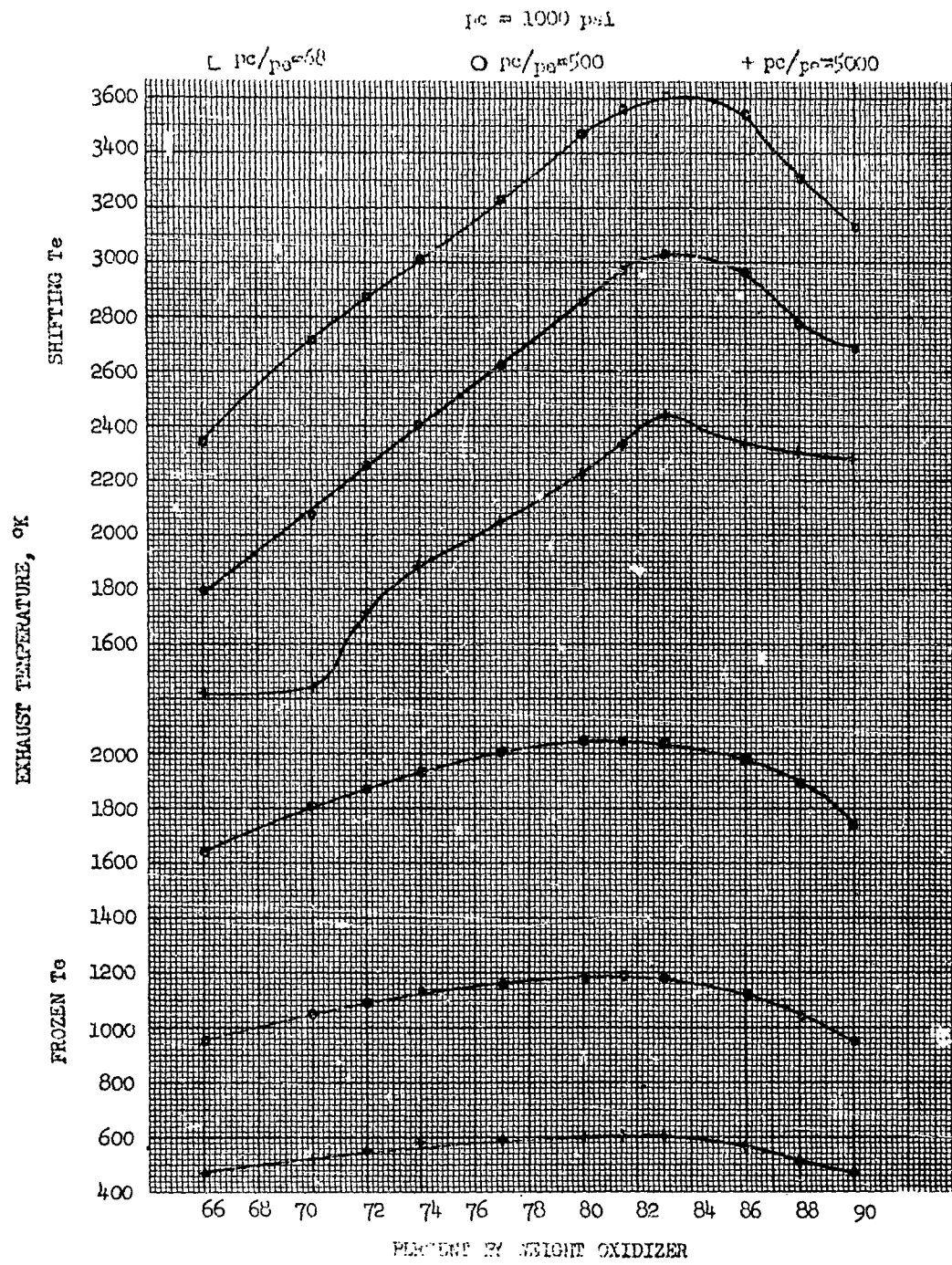
$\square p_c/p_e = 68$

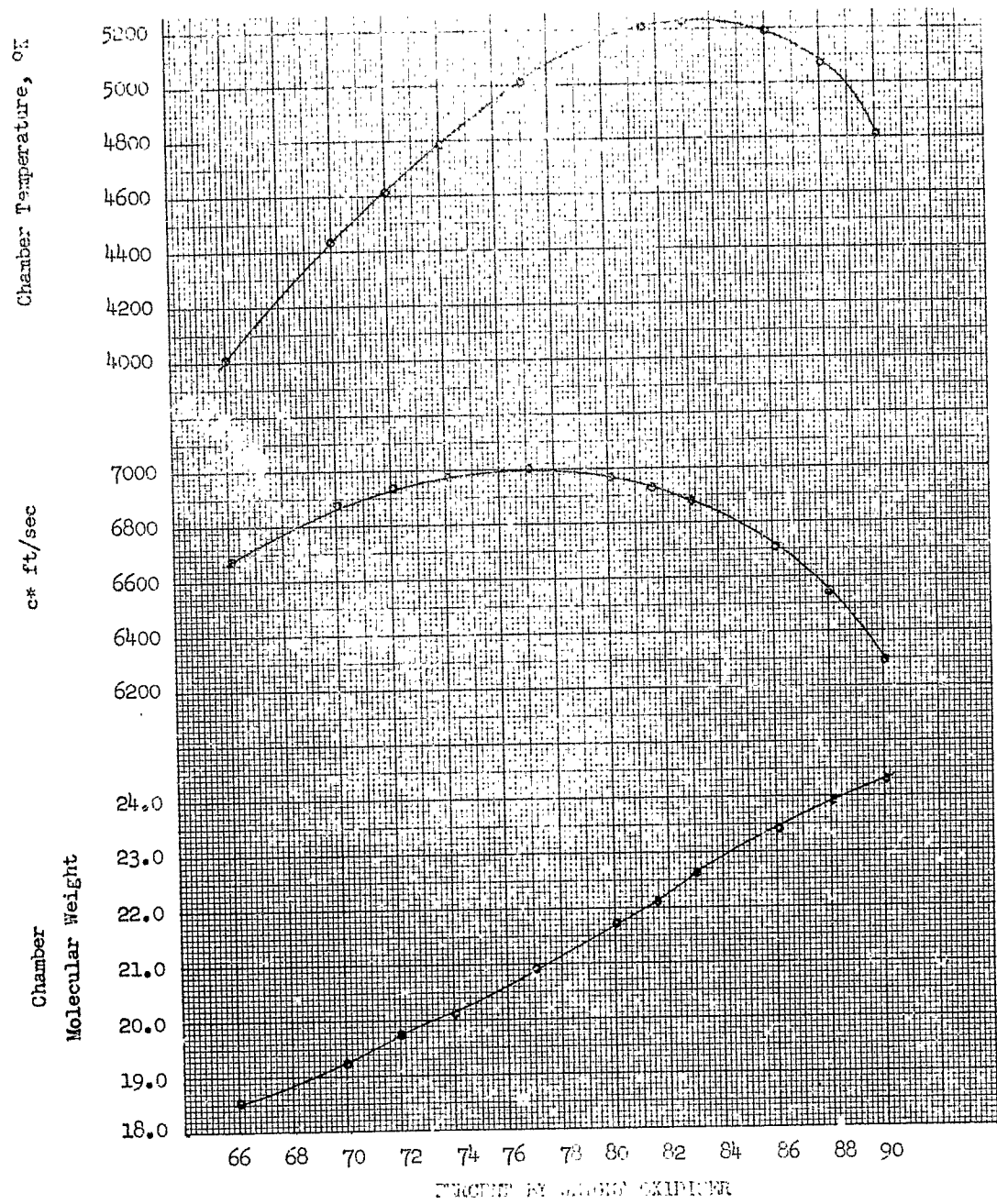
$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$

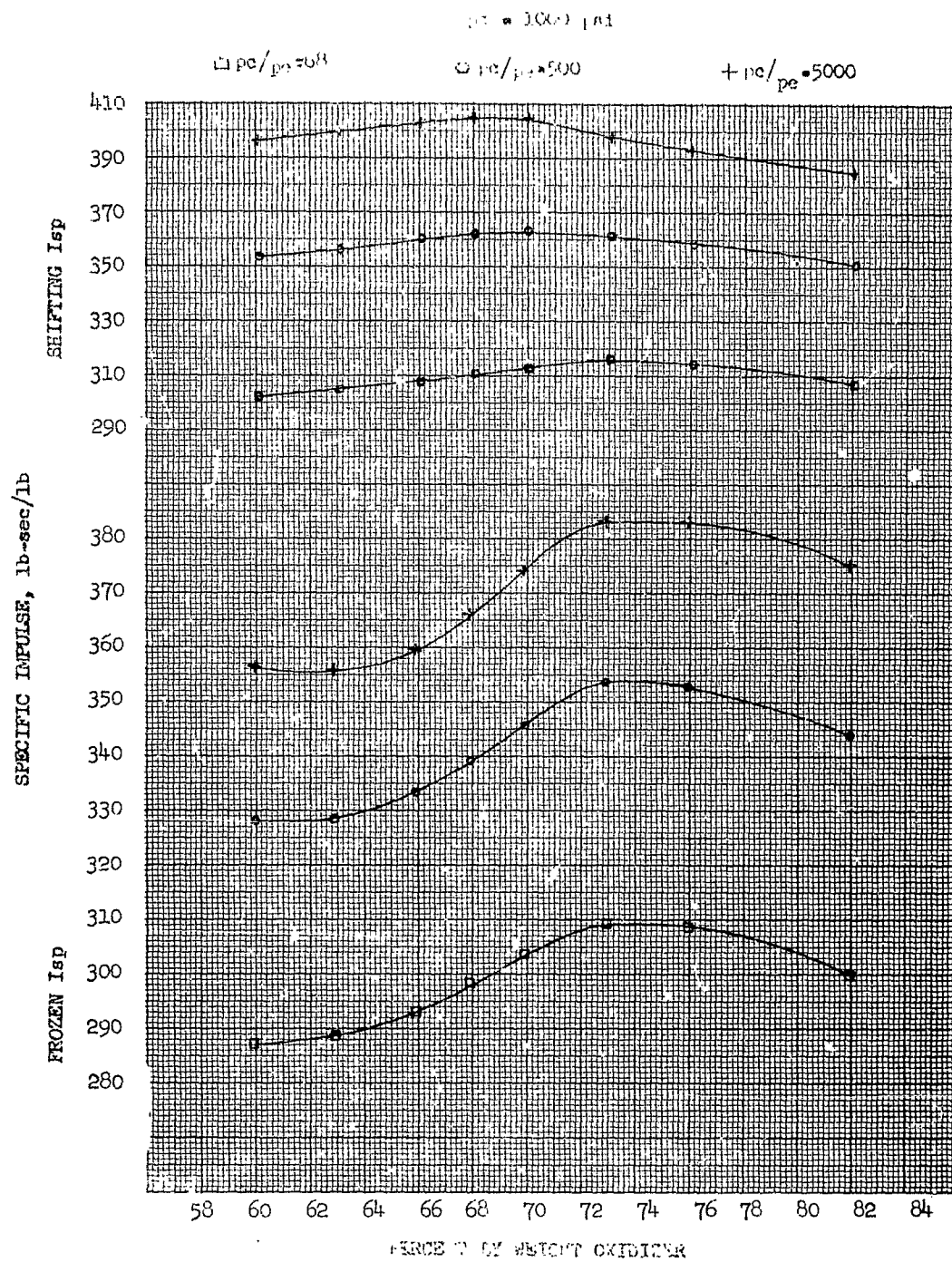


PENTABORANE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 153





PENTAFORANE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 160



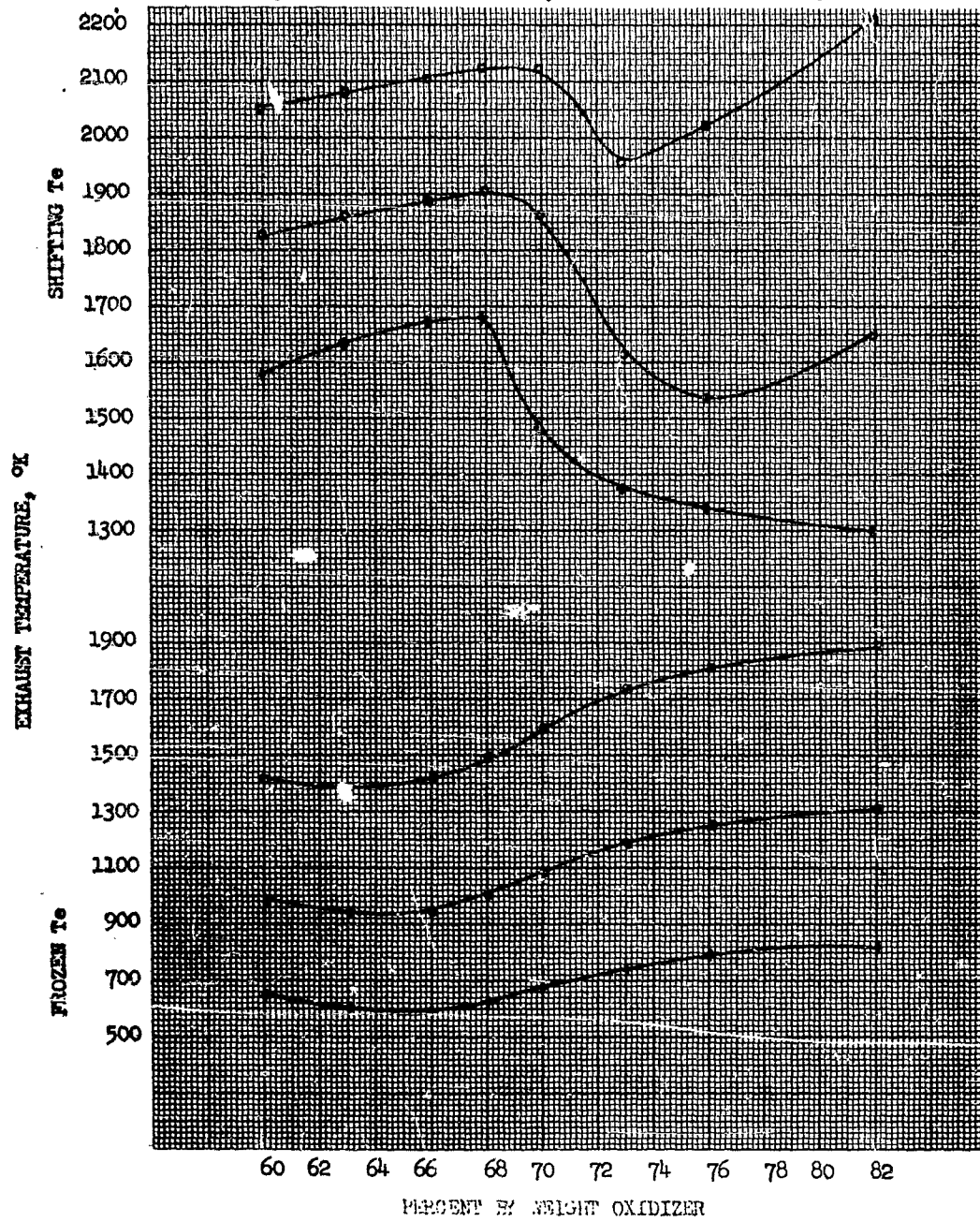
PENTABORANE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 161

$p_c \approx 1000$ psi

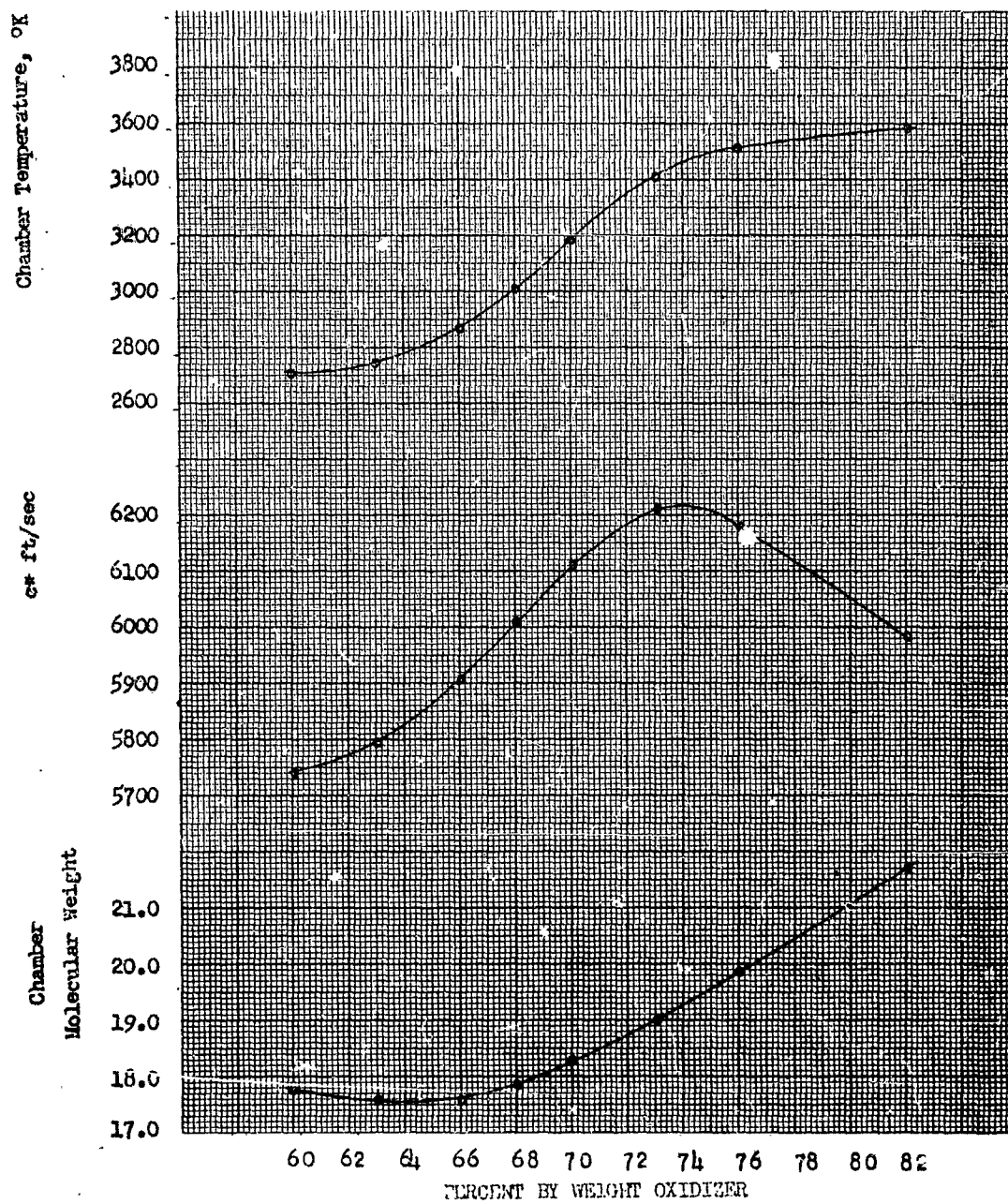
\square $p_c/p_e \approx 68$

\circ $p_c/p_e \approx 500$

$+ p_c/p_e \approx 5000$



PERFLUORACETONE-HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 152



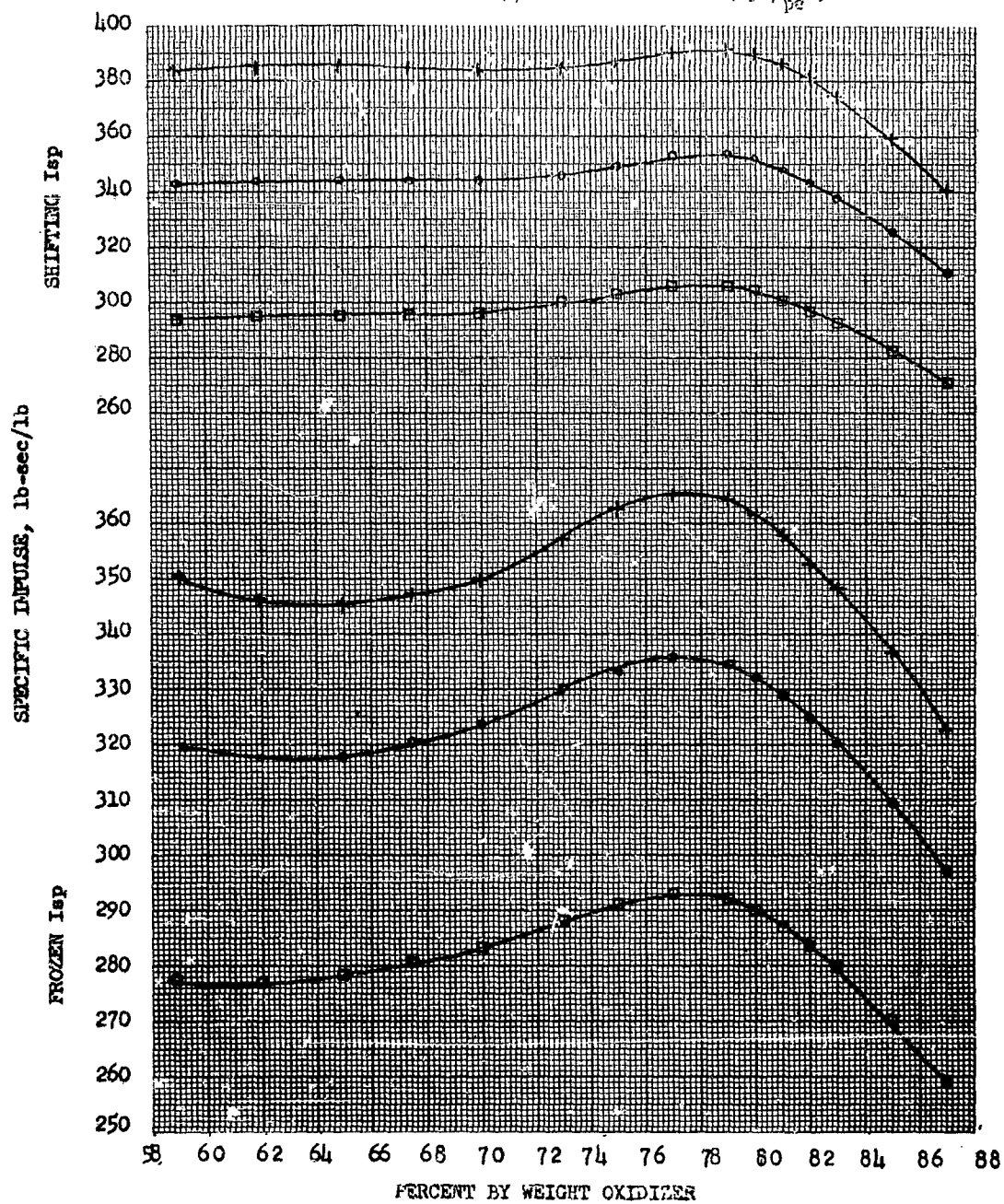
PENTABORANE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 163

$p_c = 1000 \text{ psi}$

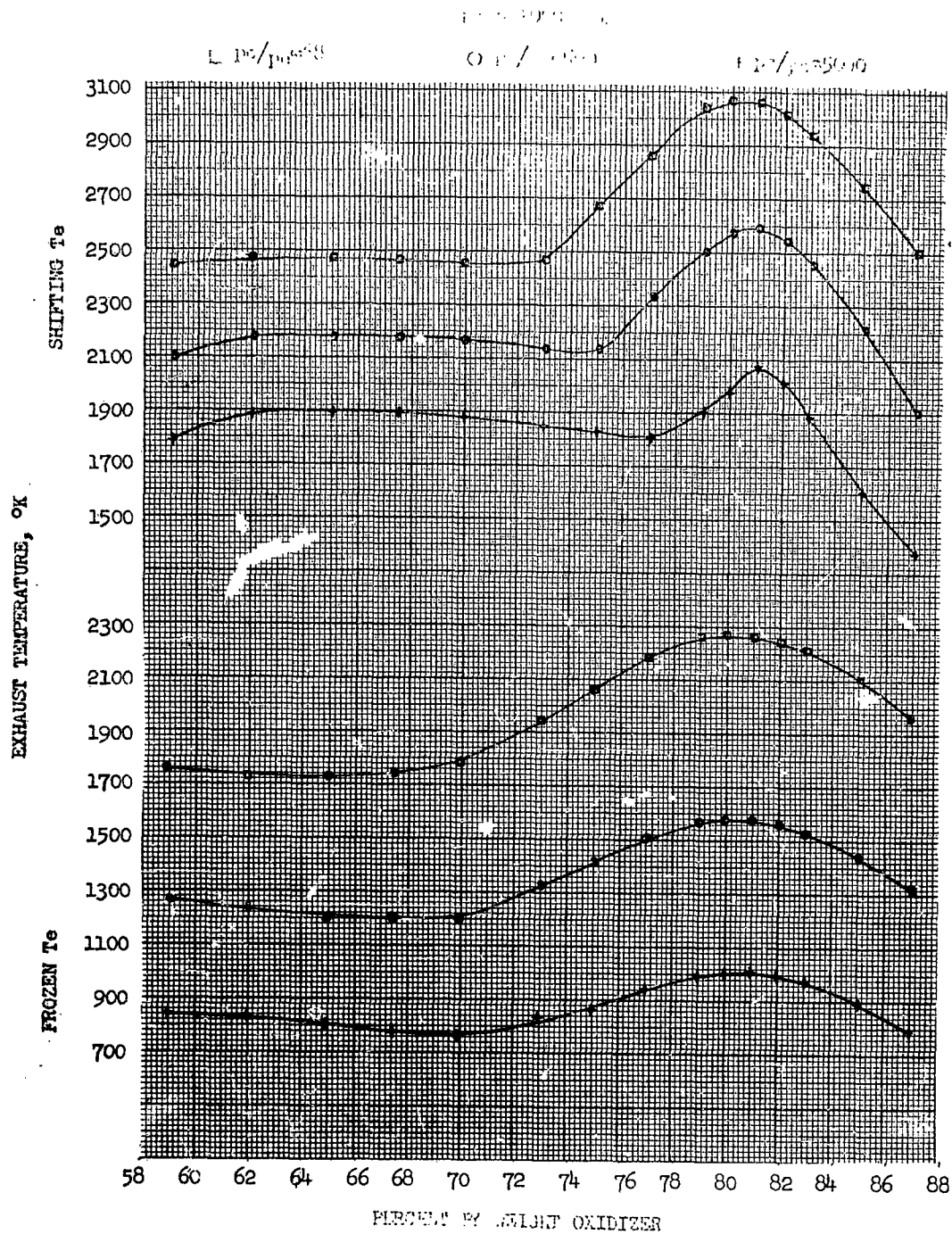
$\square p_c/p_0 = 68$

$\circ p_c/p_0 = 500$

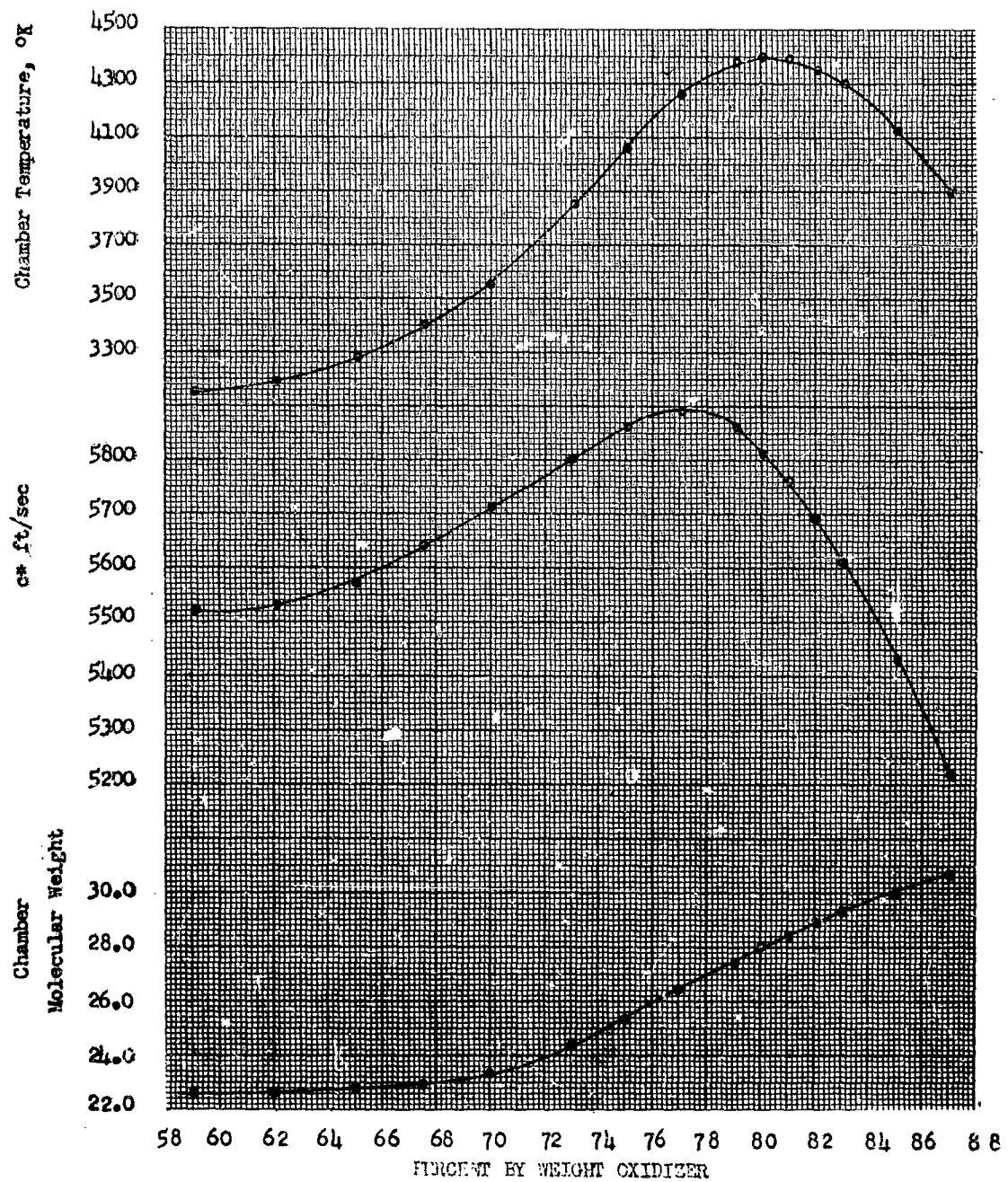
$+ p_c/p_0 = 5000$



PENTABORANE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 104



PERFORMANCE - NITROCEL TERMOXIDE PERFORMANCE CURVES FIGURE 105



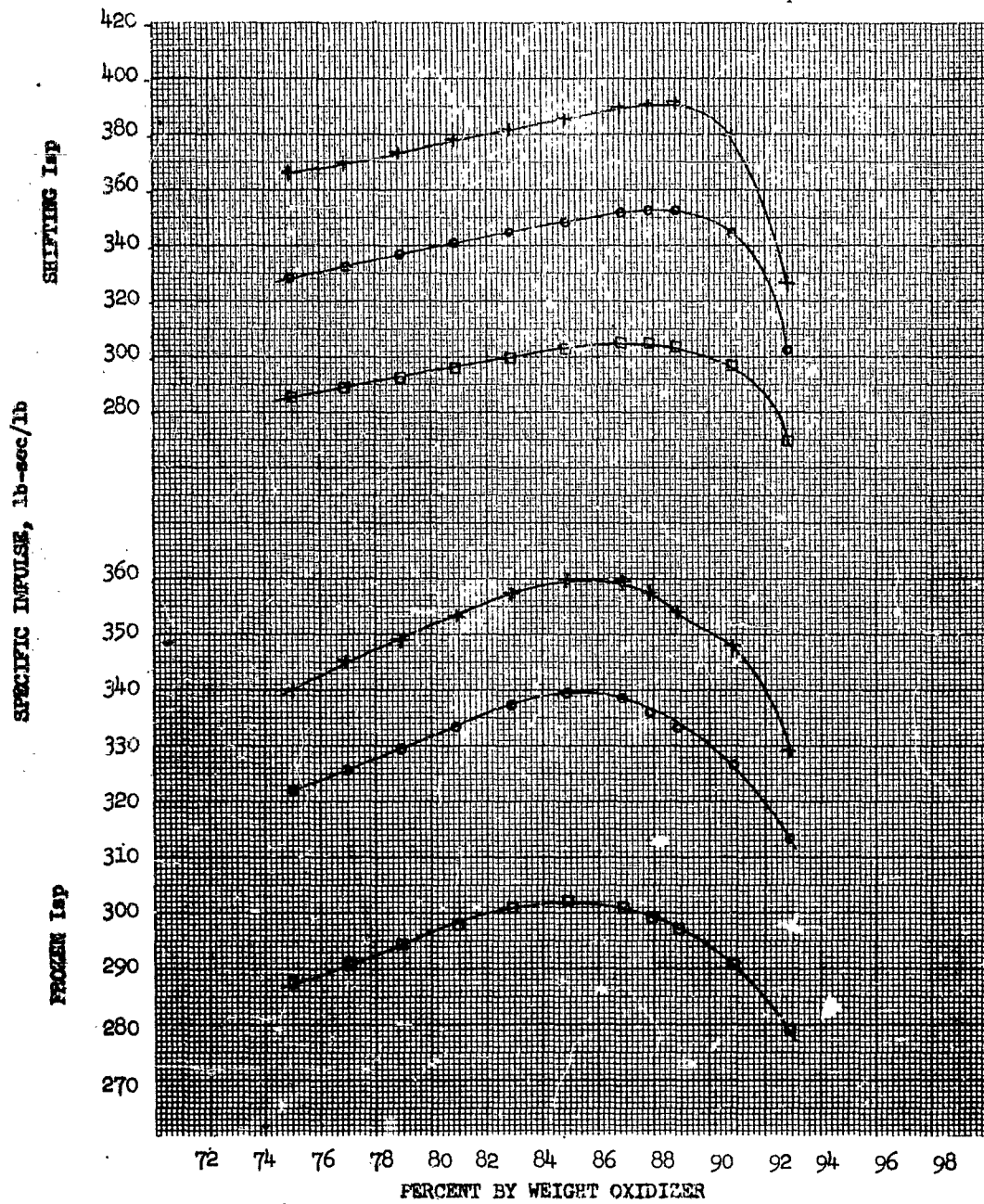
PENTABORANE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 166

$p_c = 1000 \text{ psi}$

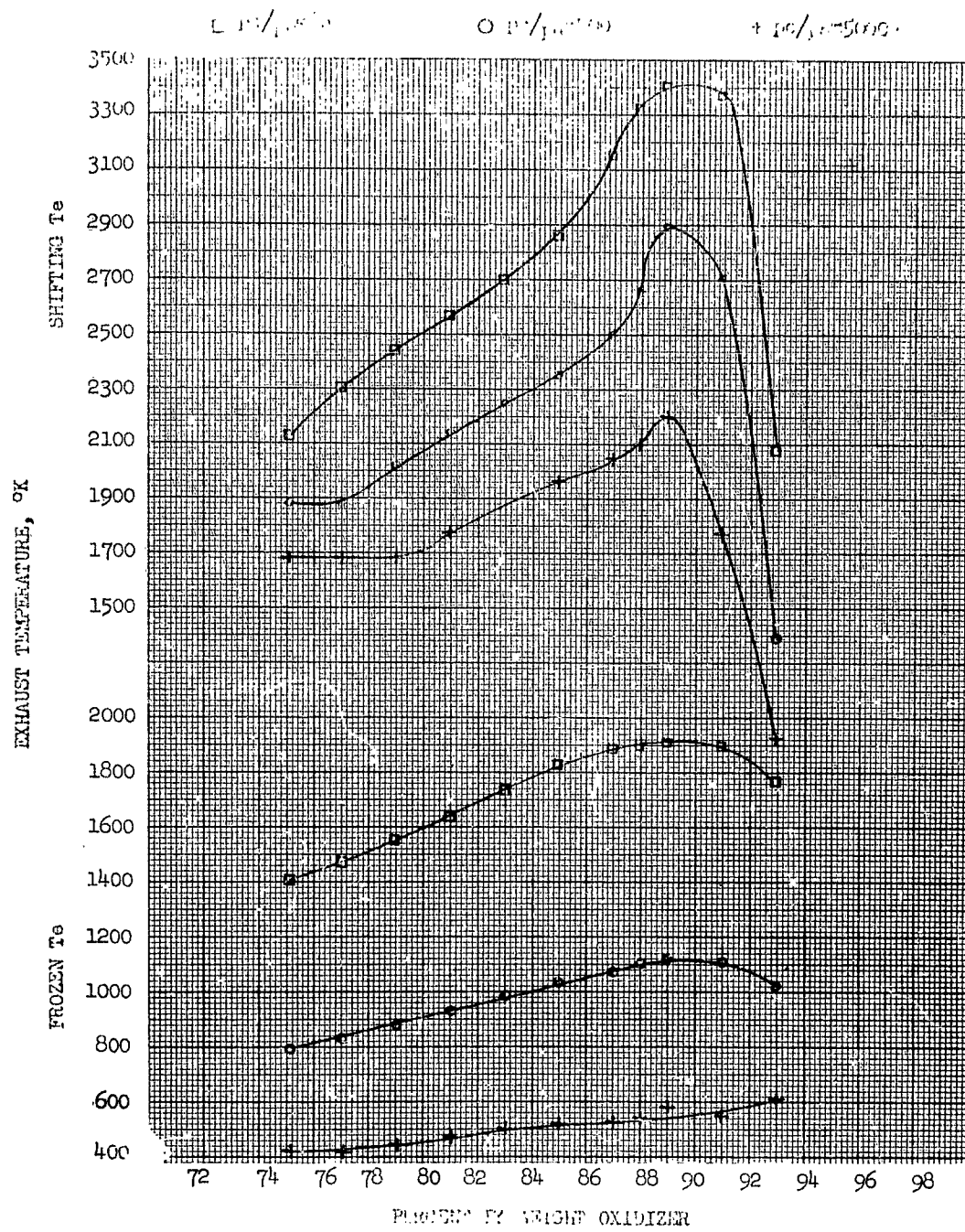
$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

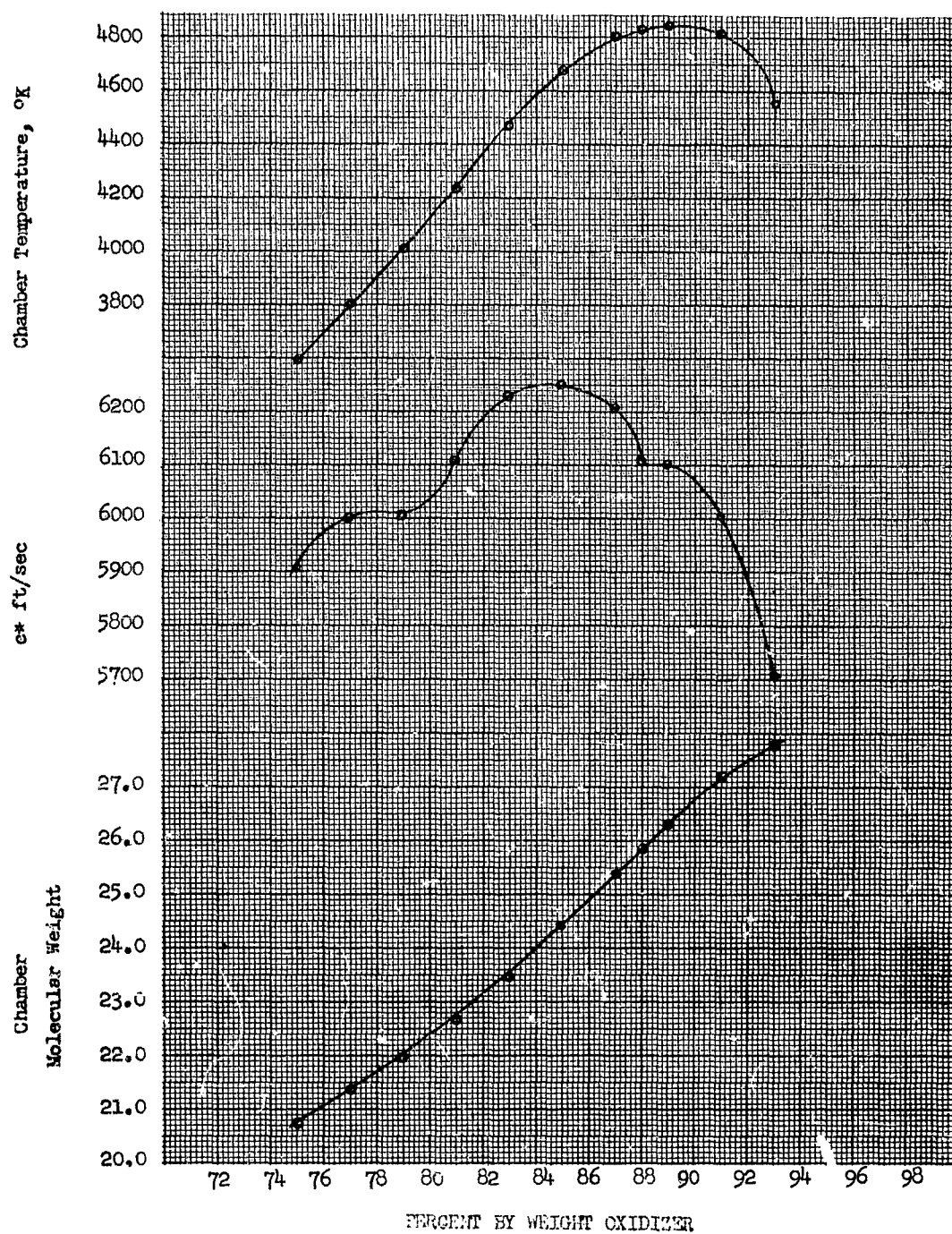
$+ p_c/p_e = 5000$



PENTABORANE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 167



PENTAFORANE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 168



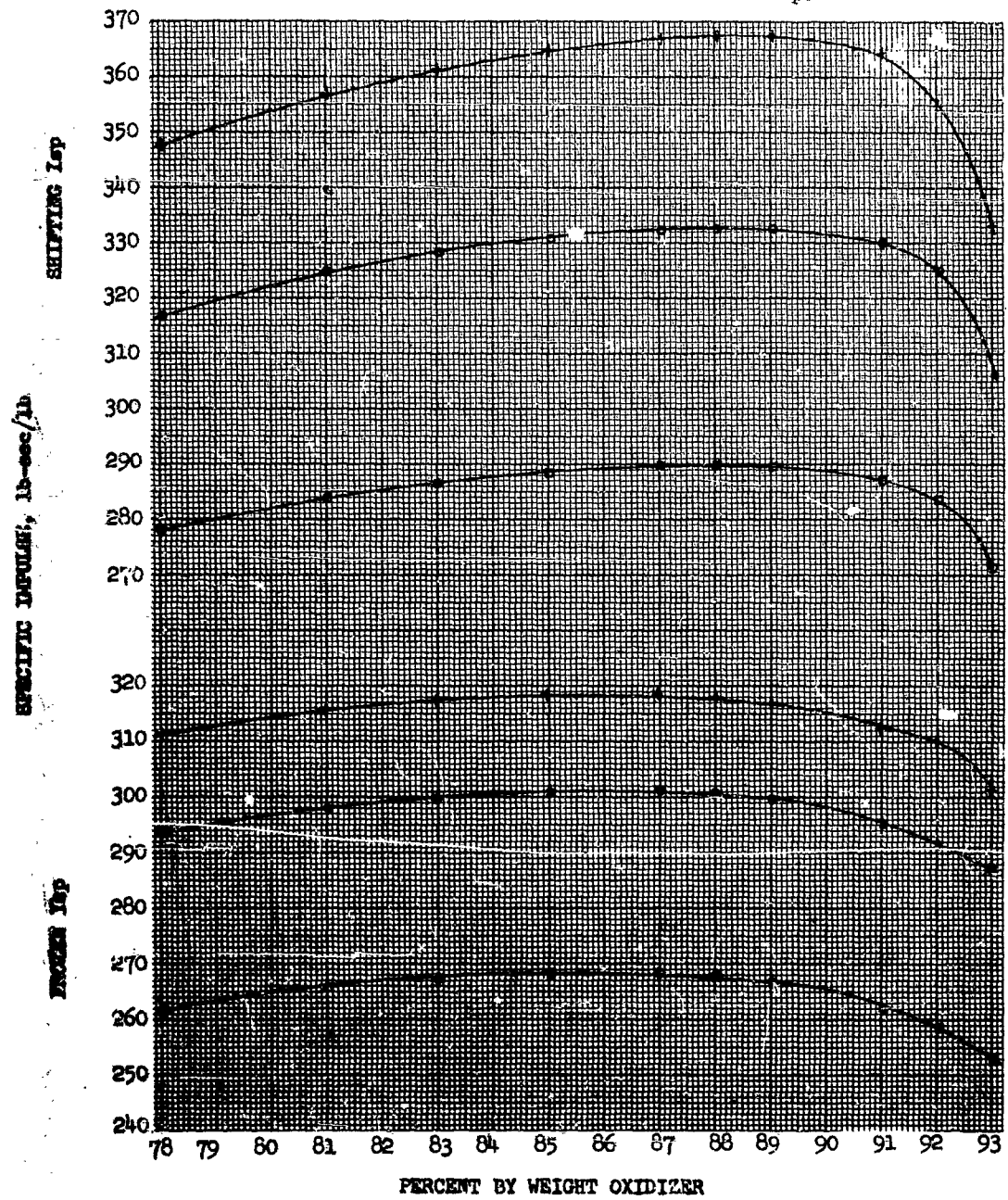
PENTABORANE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 169

pc = 1000 psi

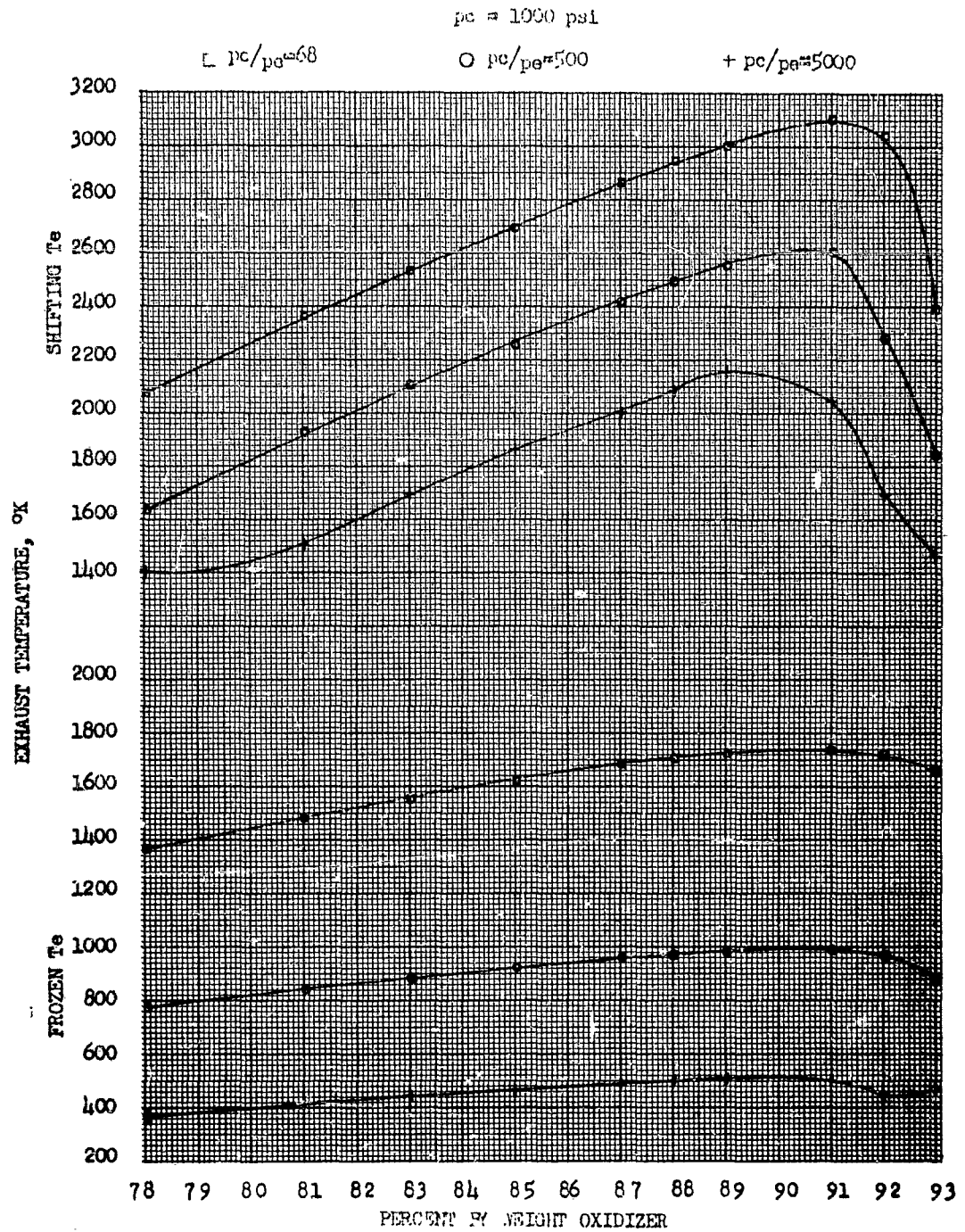
□ pc/pe = 68

○ pc/pe = 500

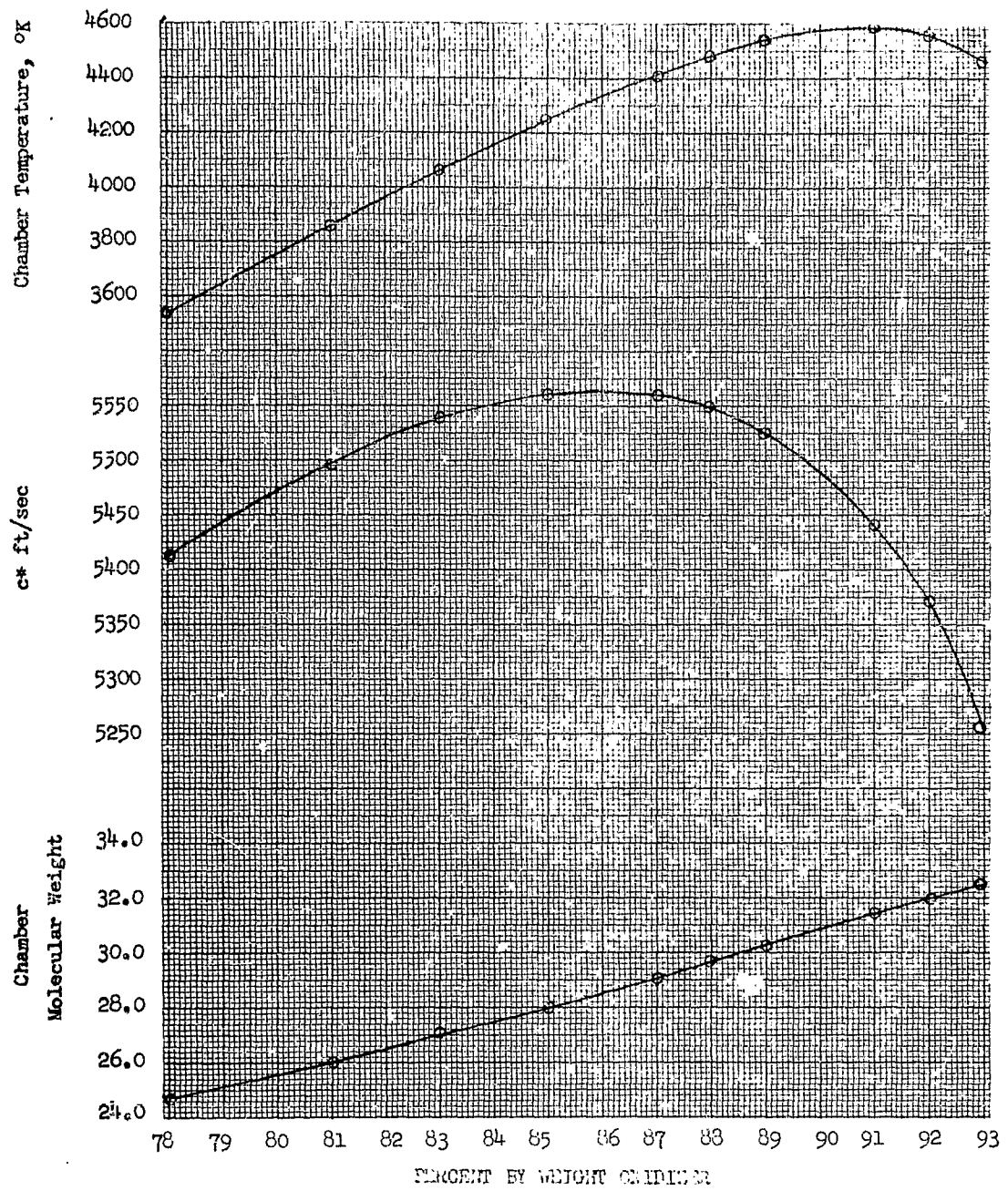
+ pc/pe = 5000

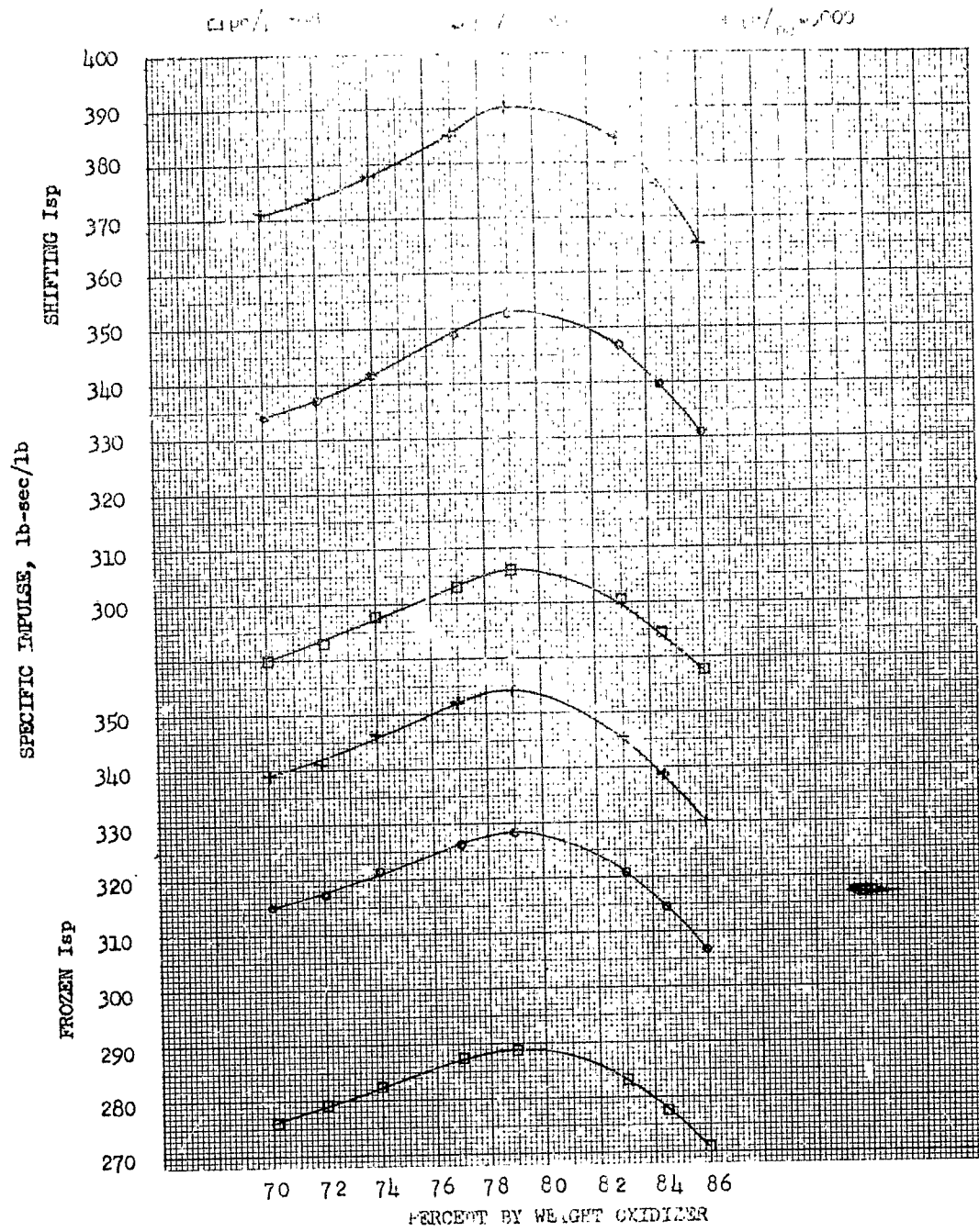


PENTABORANE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 170



PENTABORANE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 171





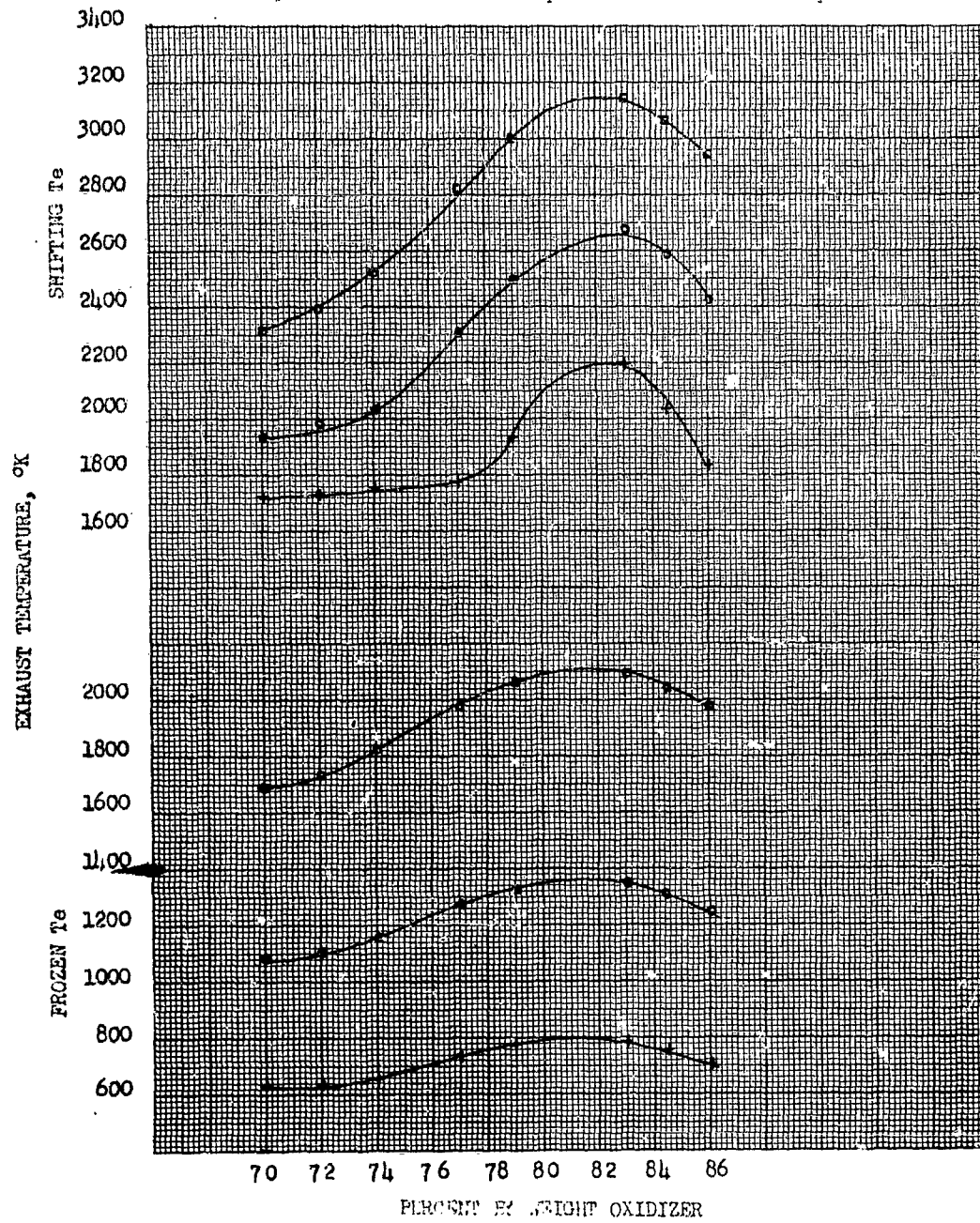
PENTABORANE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 173

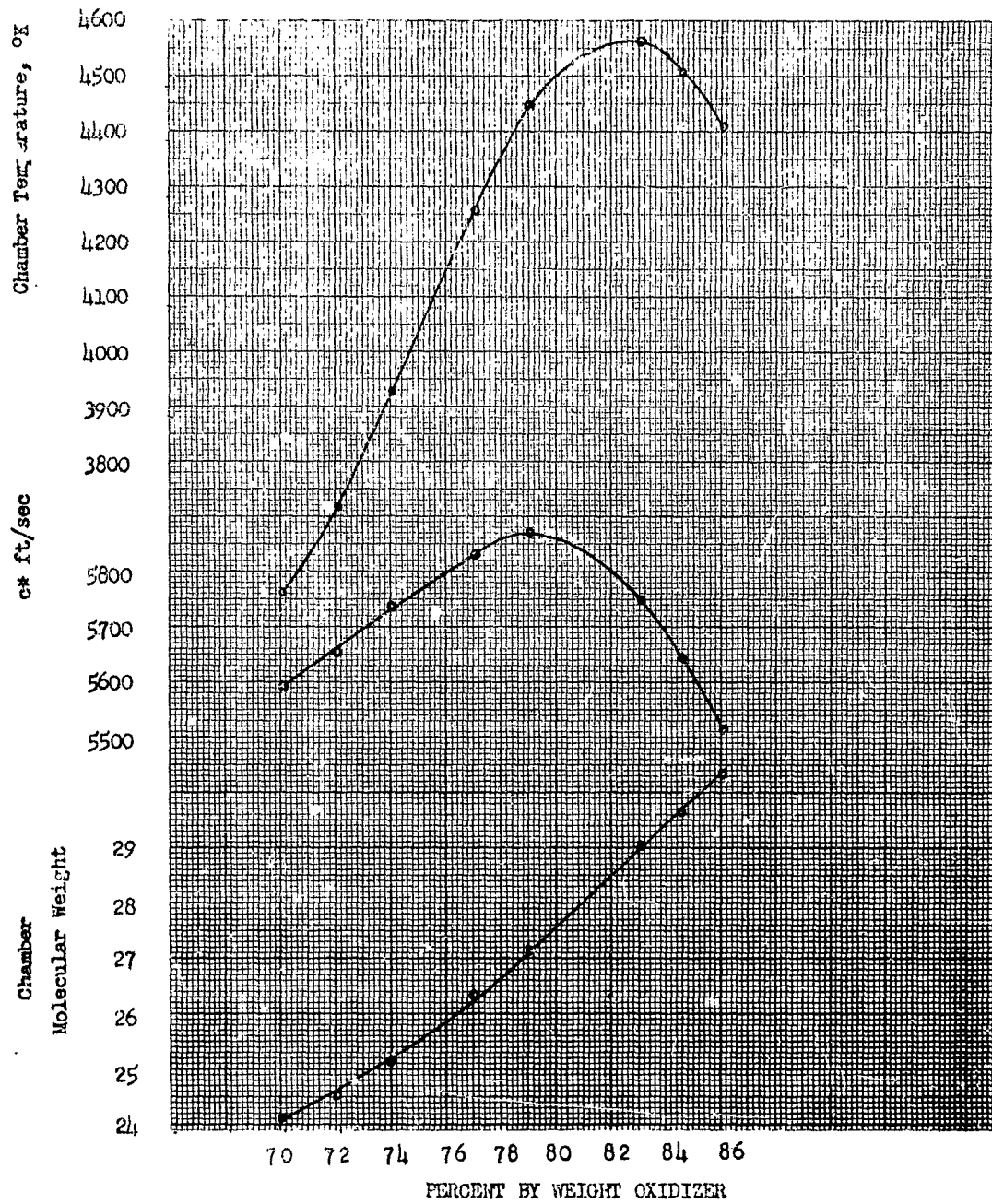
pc = 1000 lbf

□ pc/po=68

○ pc/po=500

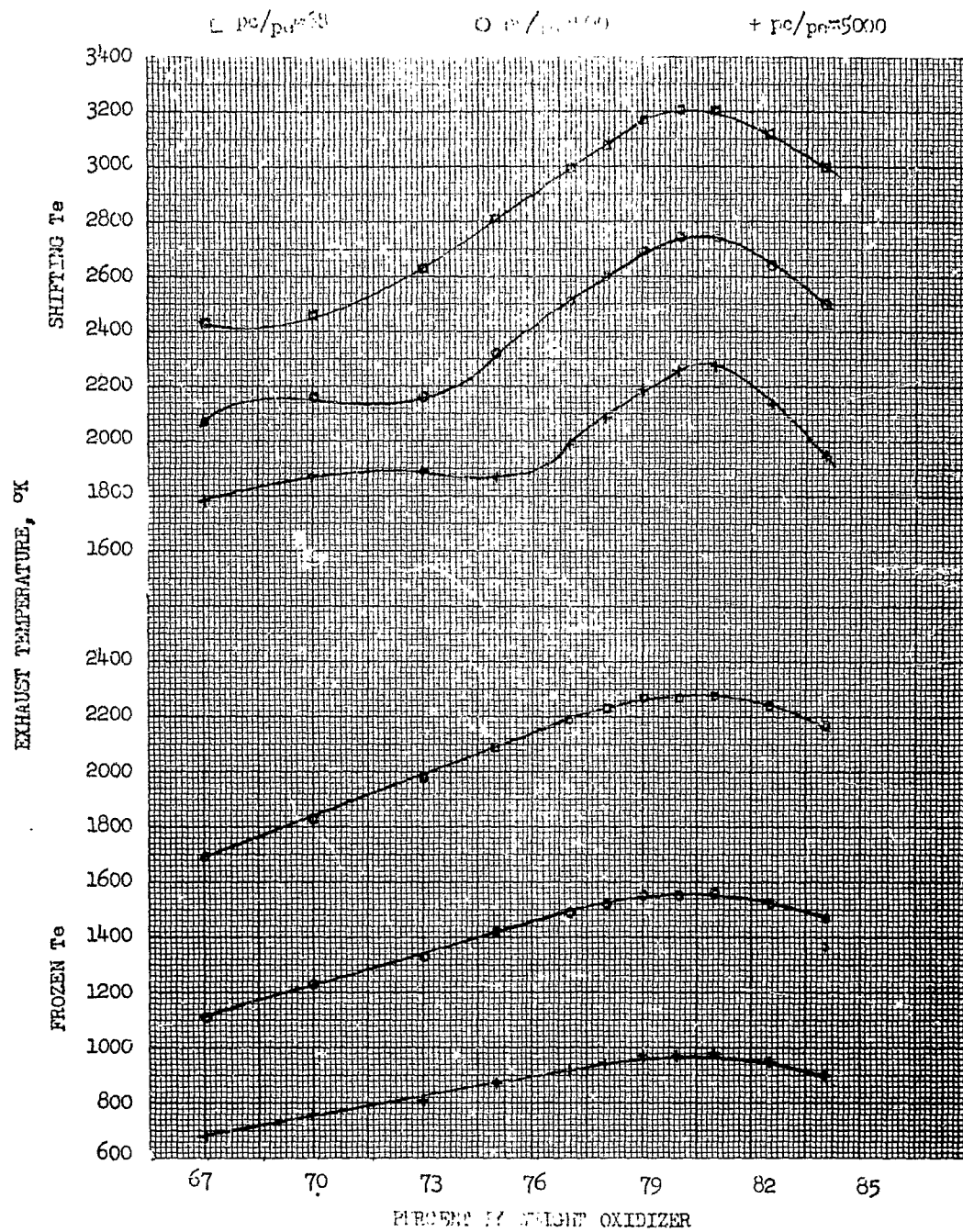
+ pc/po=5000



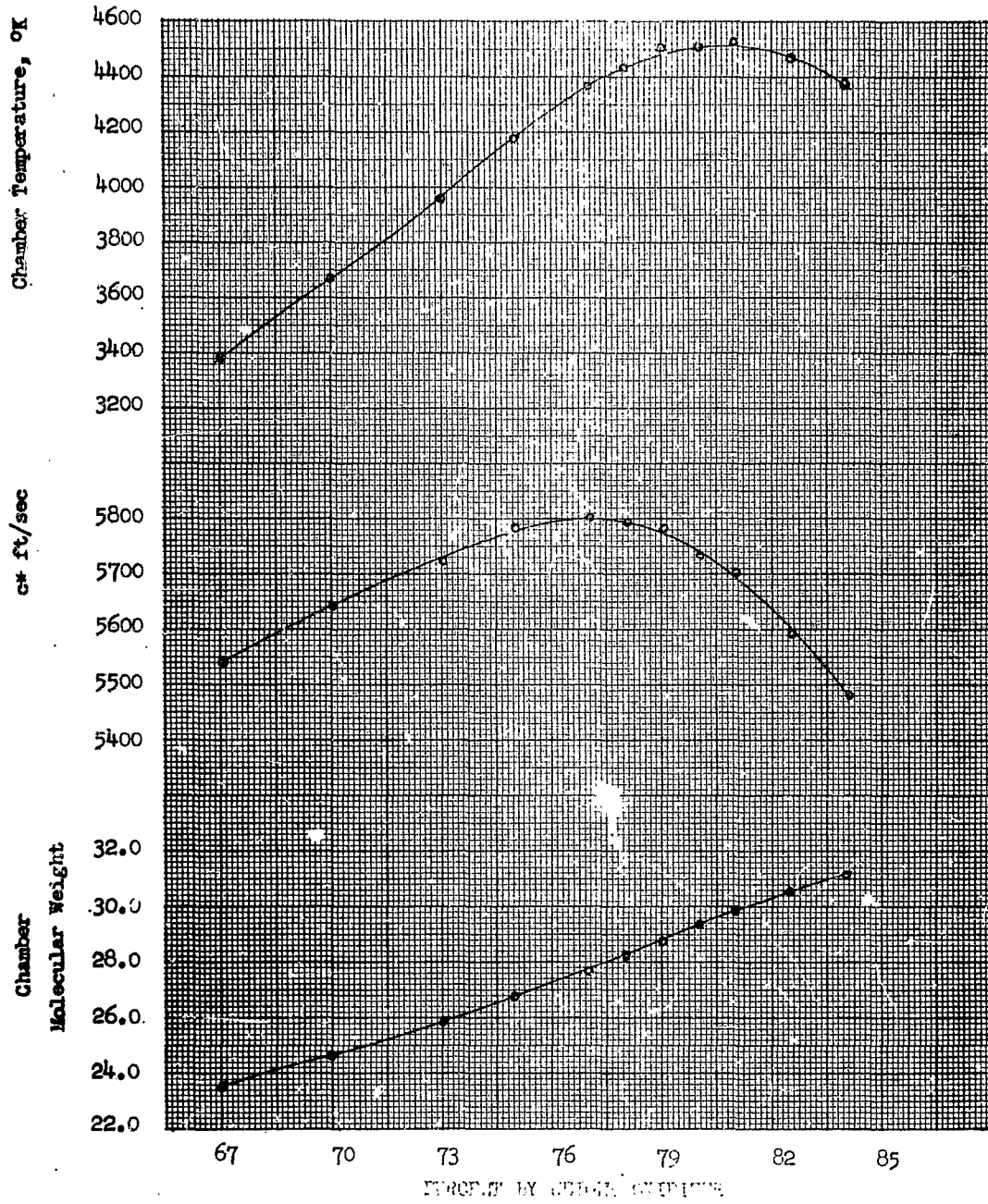


[illegible]

PENTABORANE - NITROMETHAN PERCHLORATE PERFORMANCE CURVES FIGURE 176



PENTABORANE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 177



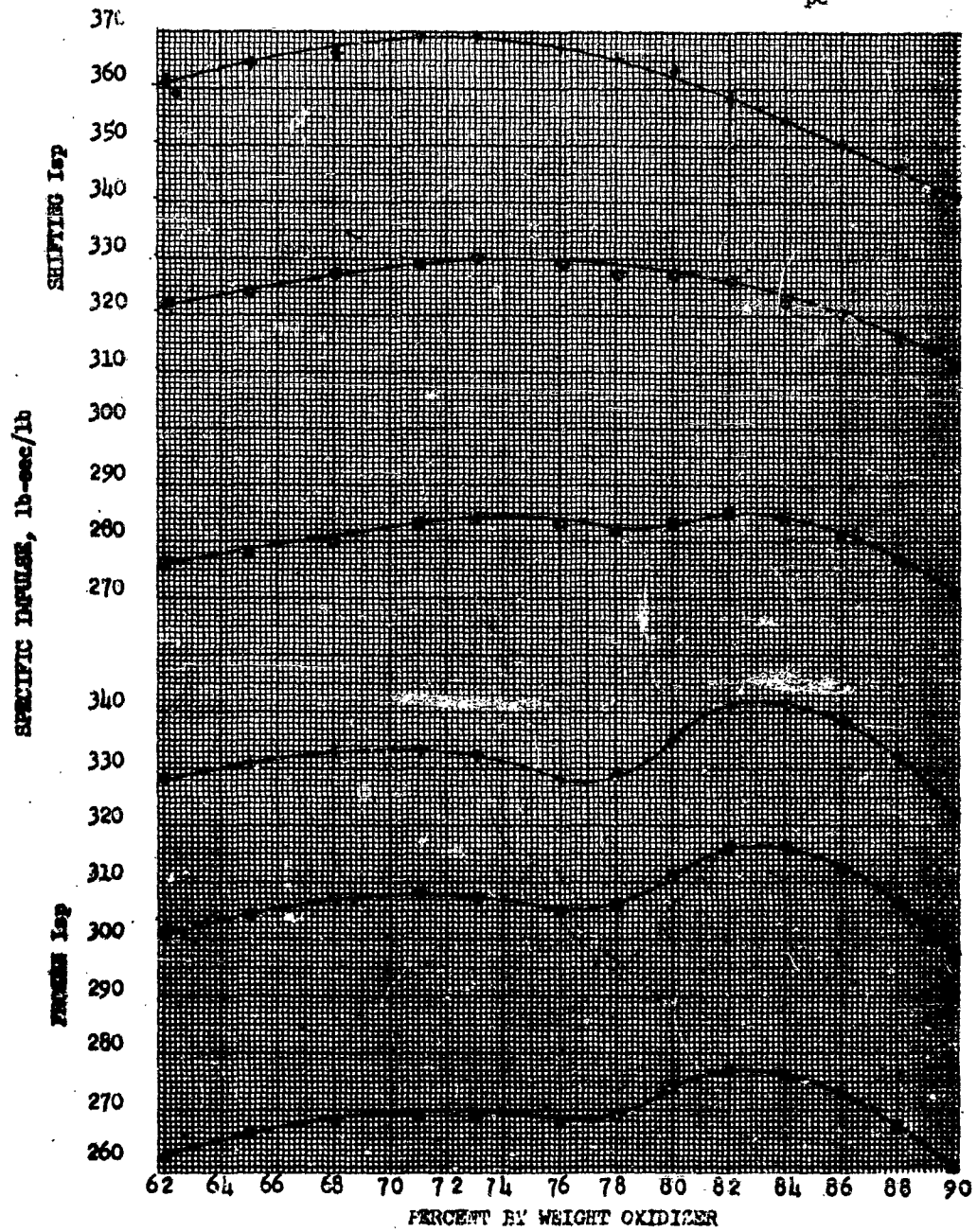
PENTABORANE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 178

pc = 1000 psi

□ pc/pe = 68

○ pc/pe = 500

+ pc/pe = 5000



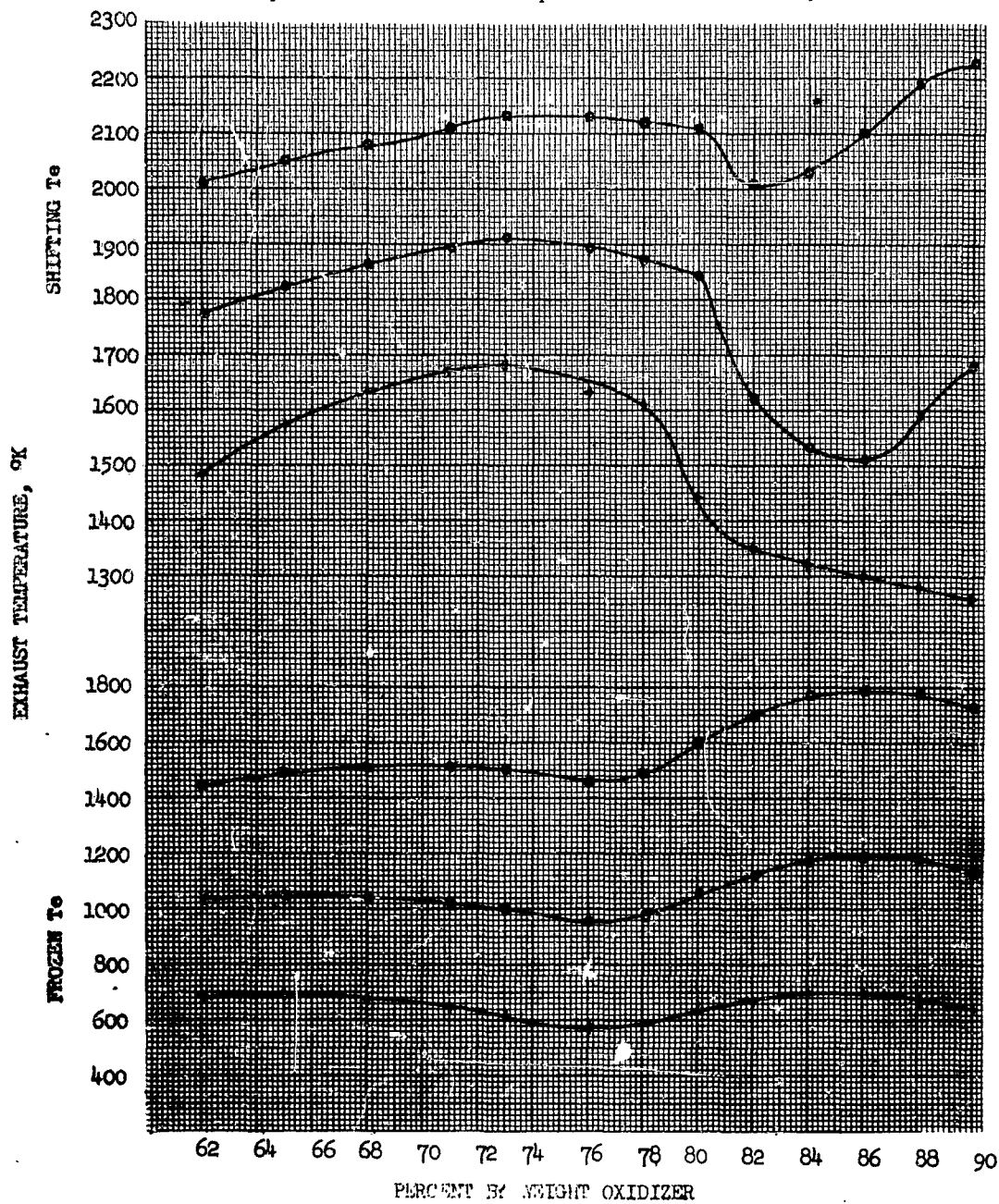
PENTABORANE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 179

$p_c \approx 1000 \text{ psi}$

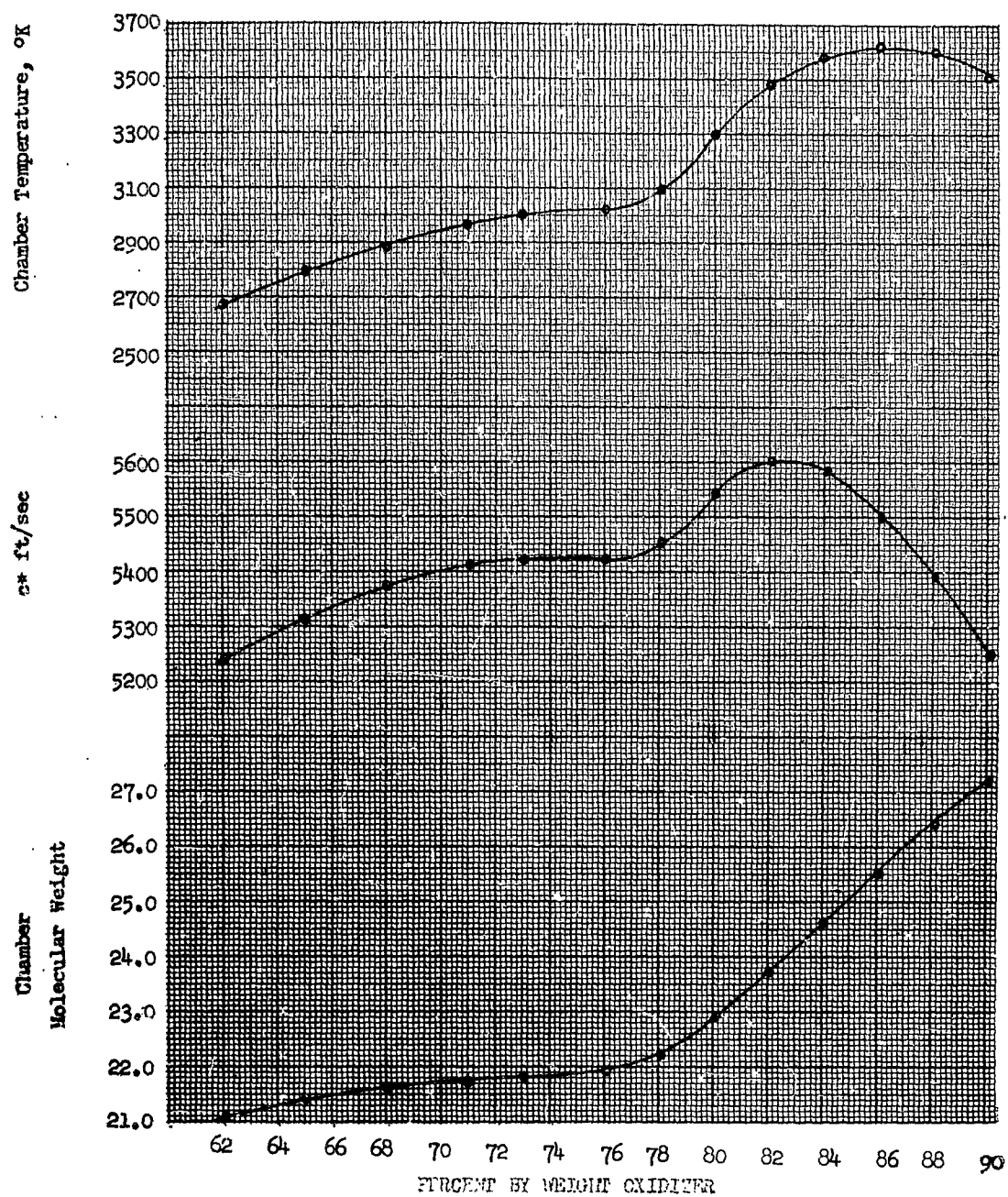
$\square p_c/p_a \approx 68$

$\circ p_c/p_a \approx 500$

$+ p_c/p_a \approx 5000$



PENTABORANE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 180



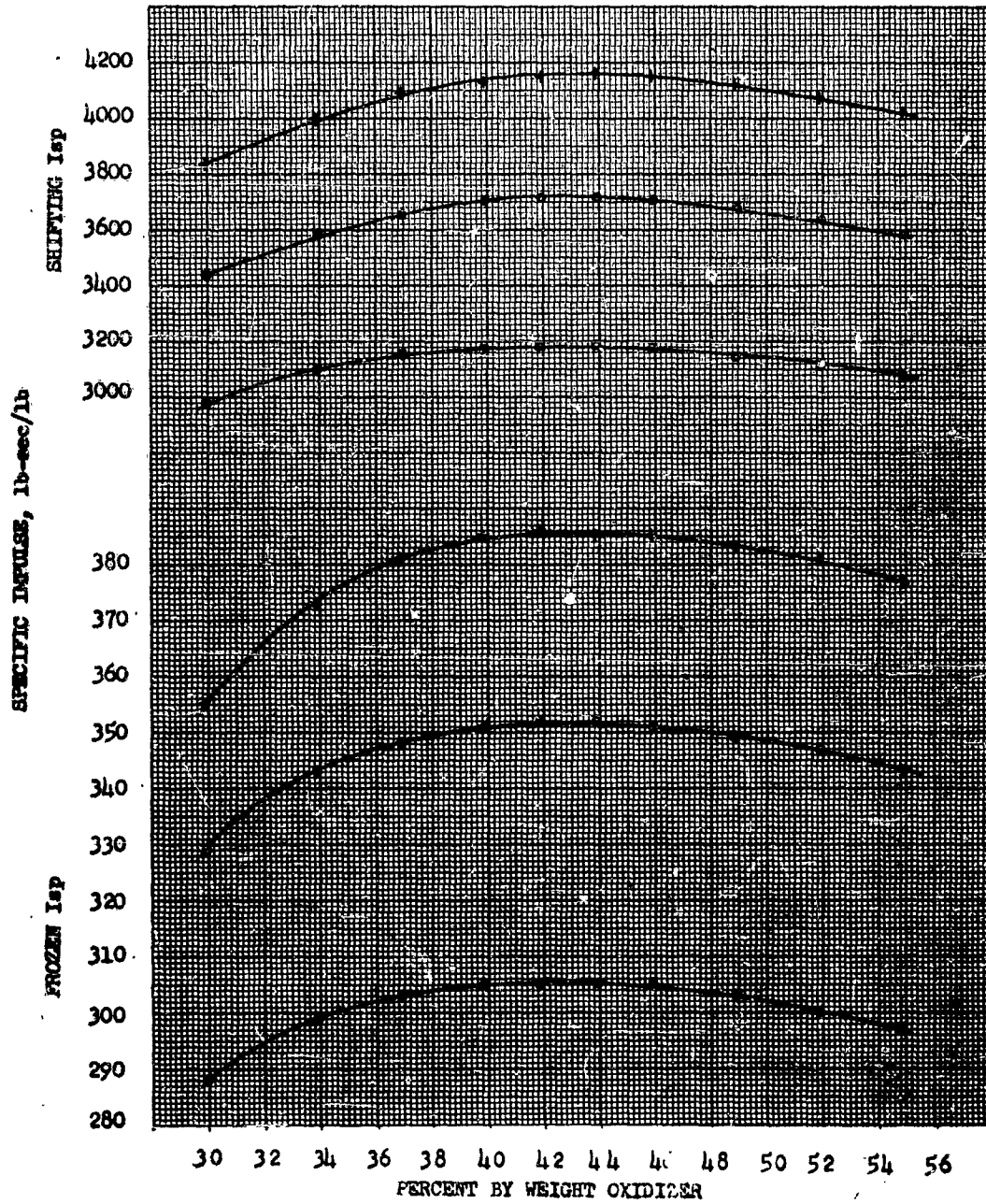
ALUMINUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 181

$p_c = 1000 \text{ psi}$

$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

$+ p_c/p_e = 5000$



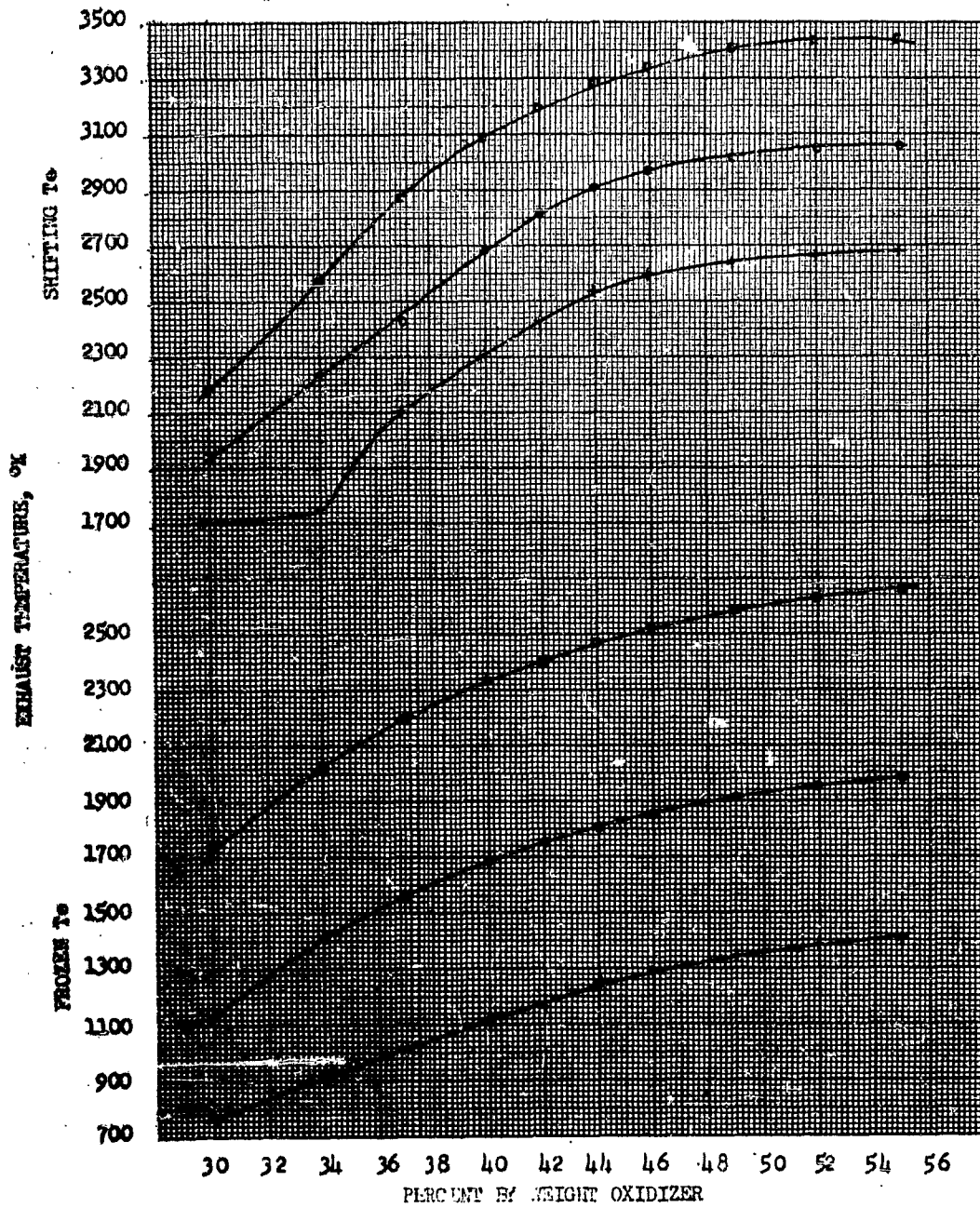
ALUMINUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 182

$p_c = 1000 \text{ psi}$

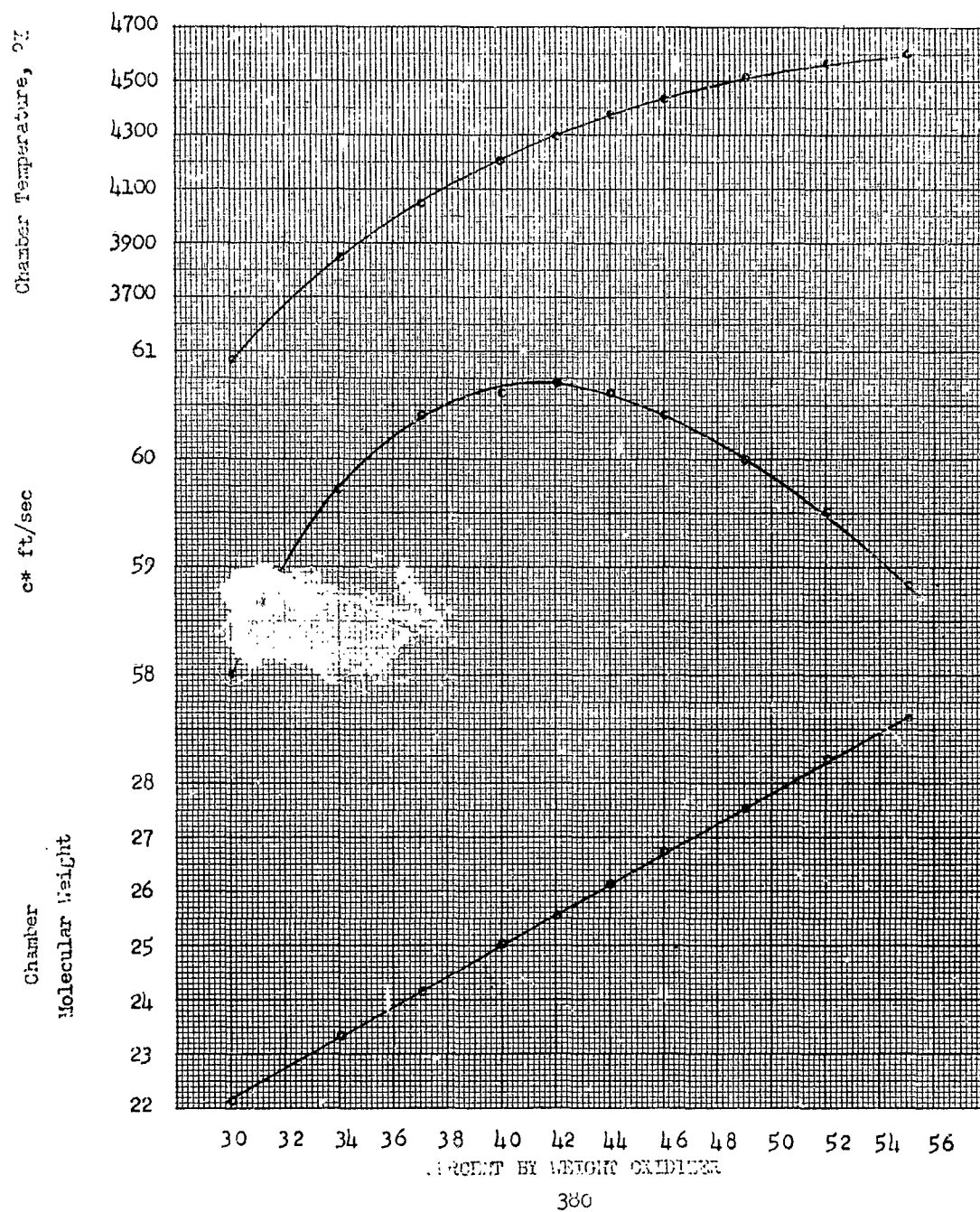
$\square p_c/p_a = 68$

$\circ p_c/p_a = 500$

$+ p_c/p_a = 5000$



ALUMINUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 183



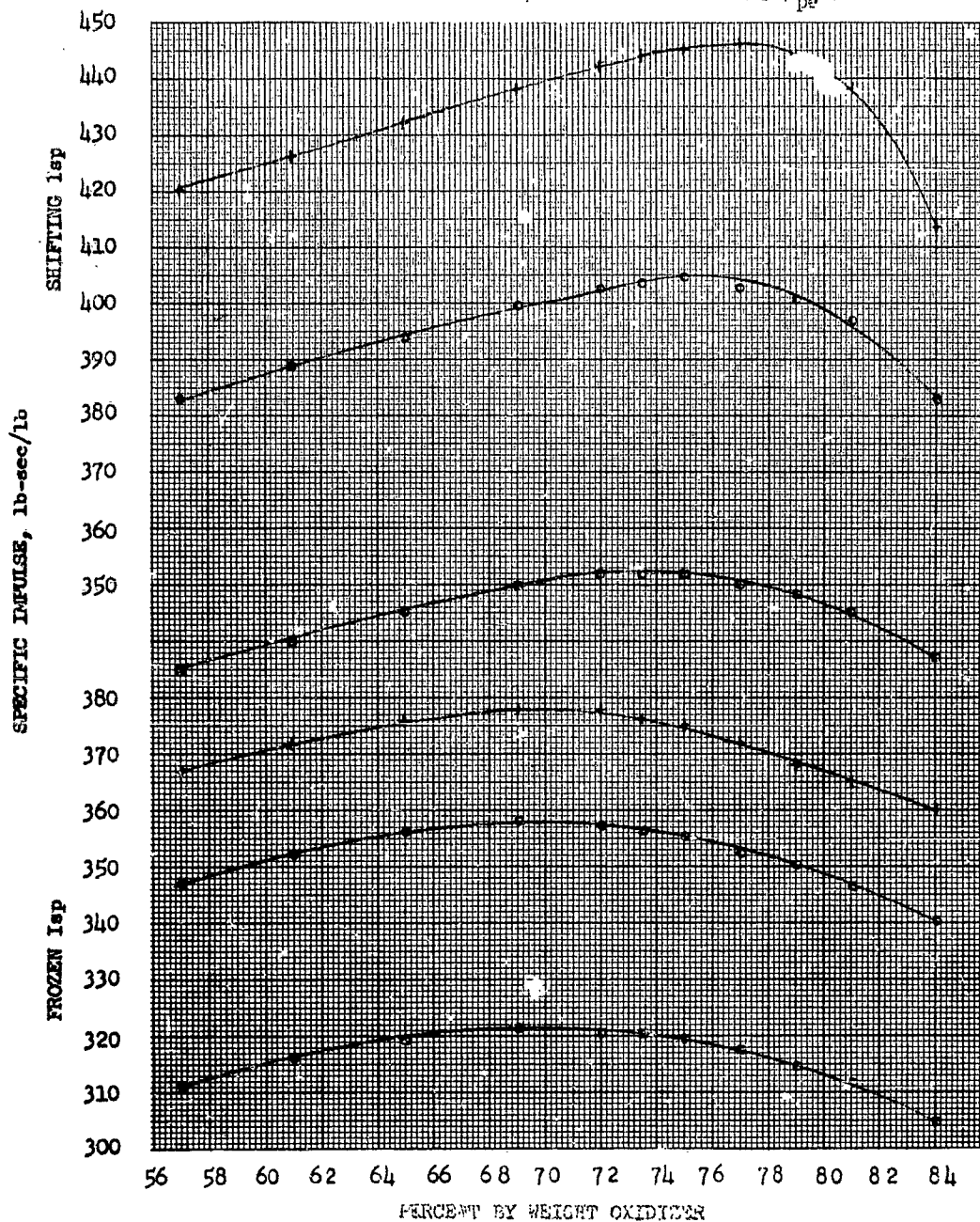
ALUMINUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 184

$p_c = 1000 \text{ psi}$

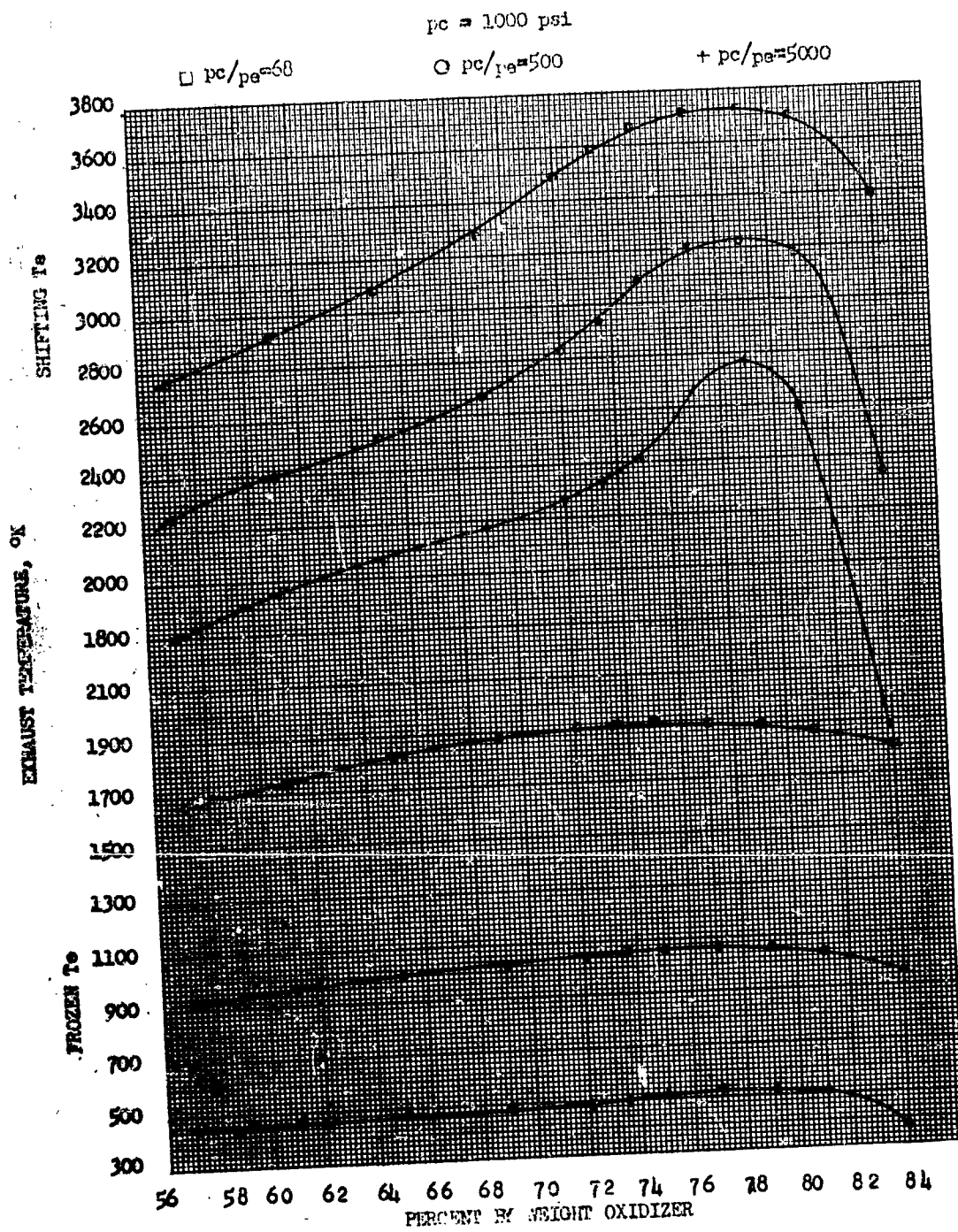
$\square p_c/p_a = 0.8$

$\circ p_c/p_a = 500$

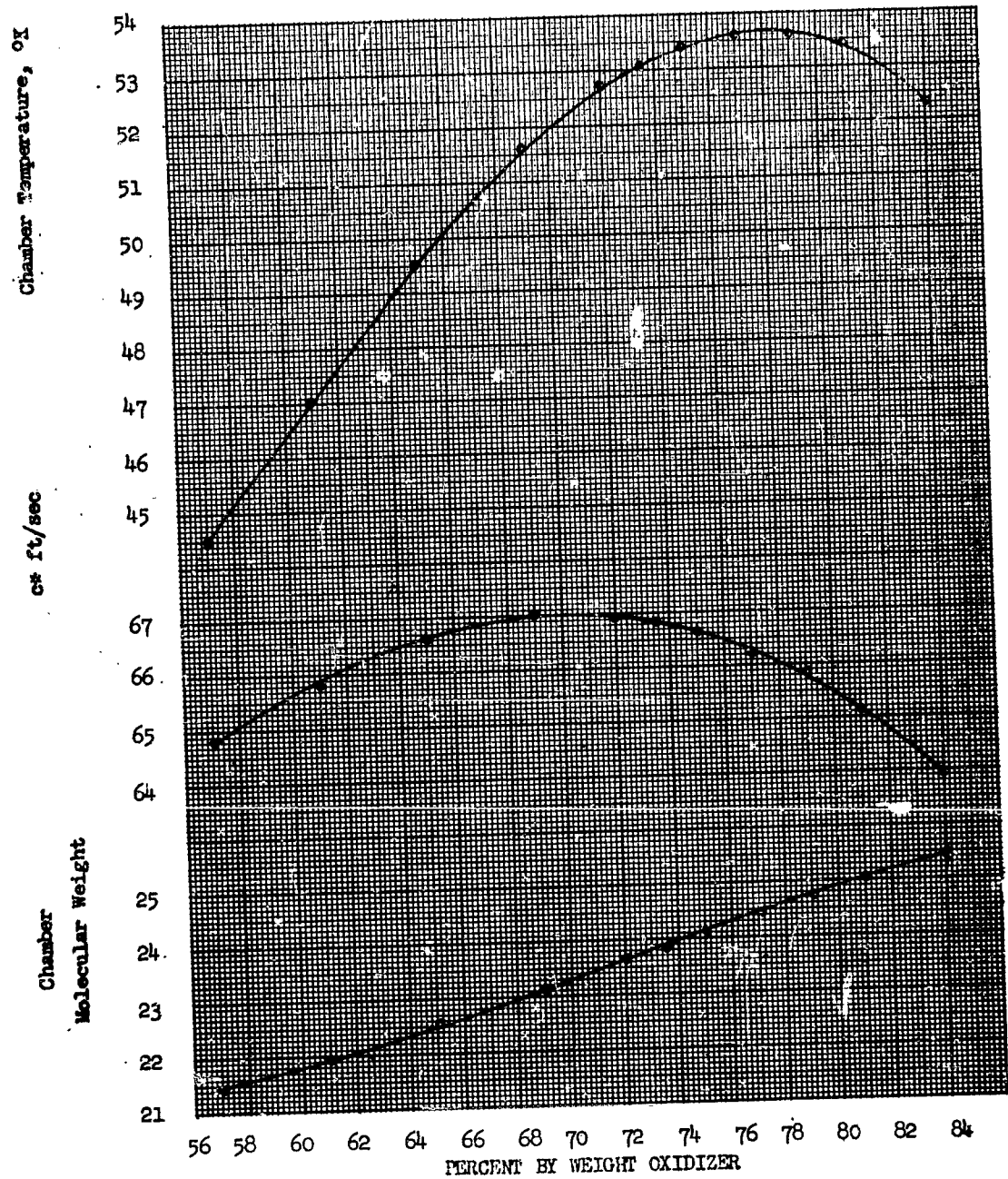
$+ p_c/p_a = 5000$



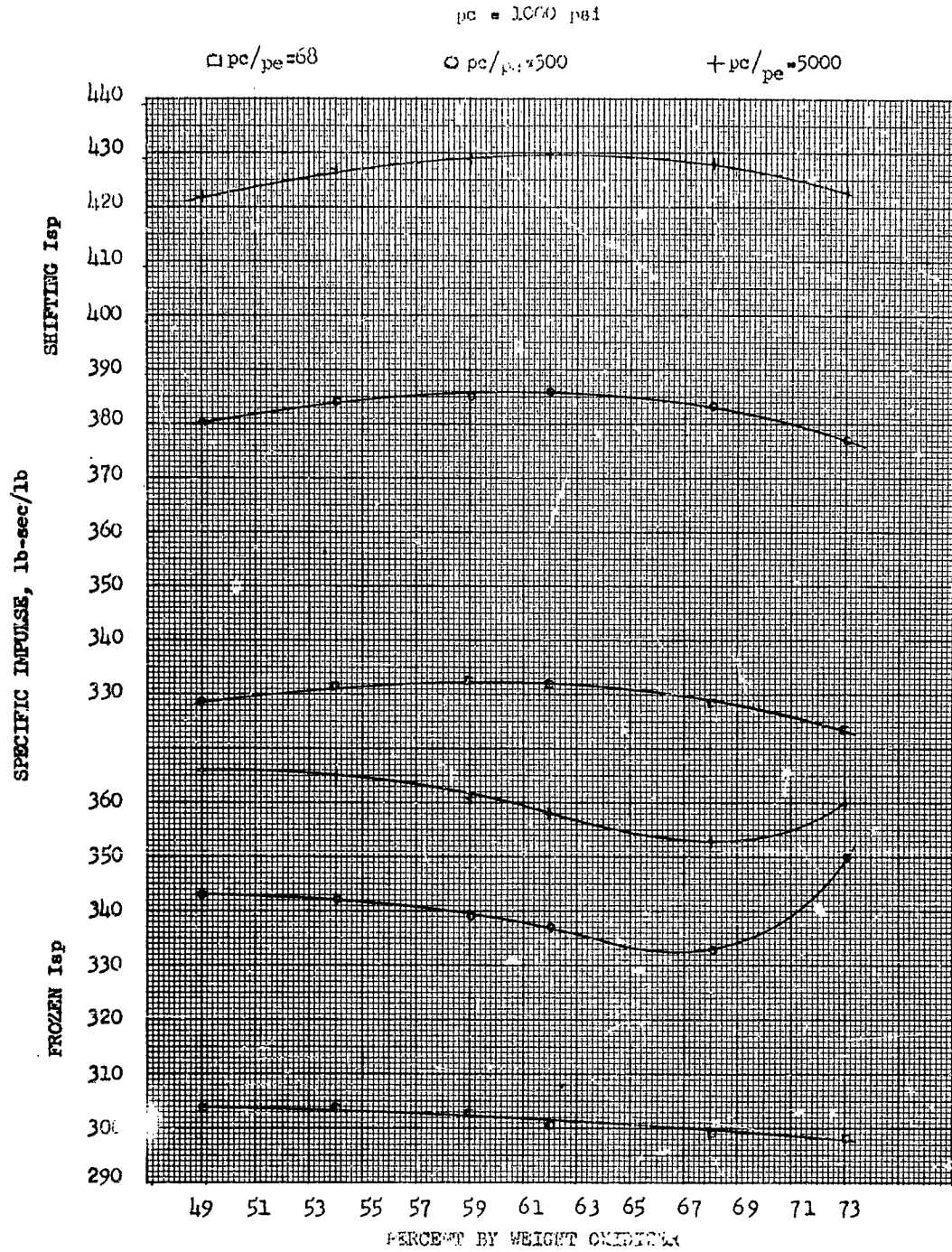
ALUMINUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 185



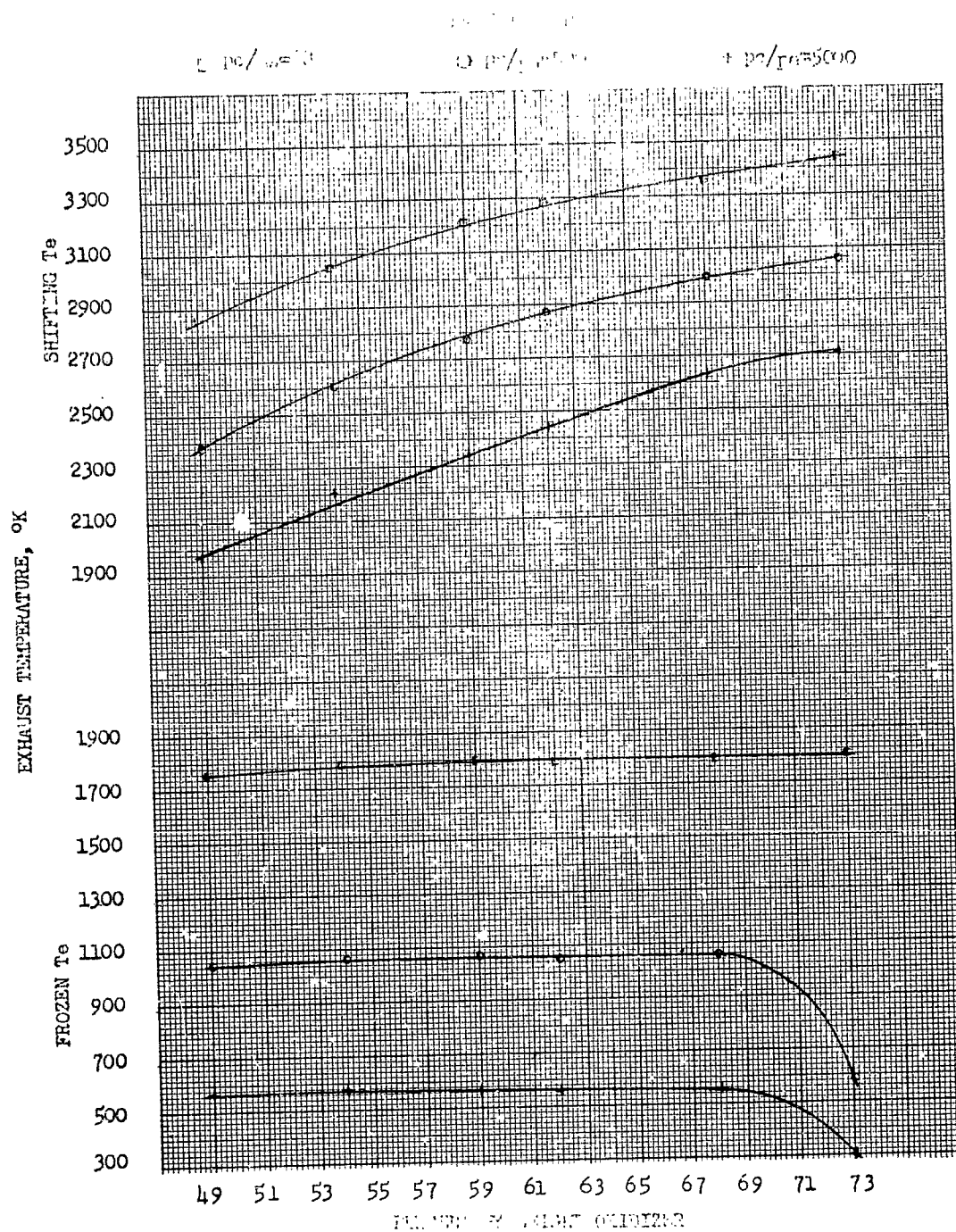
ALUMINUM HYDRIDE - LIQUID FLUORINE PERFORMANCE CURVES FIGURE 186



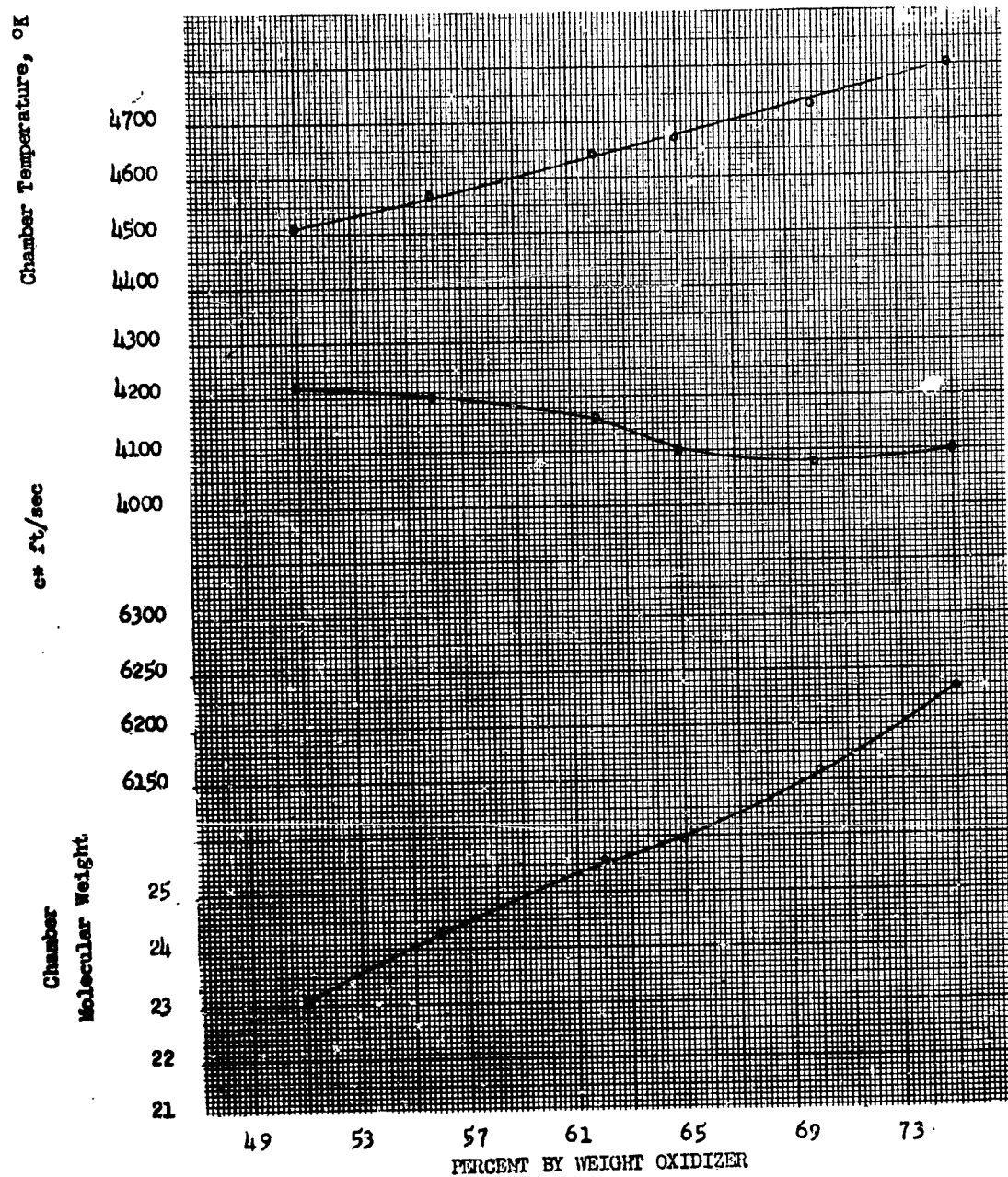
ALUMINUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 187



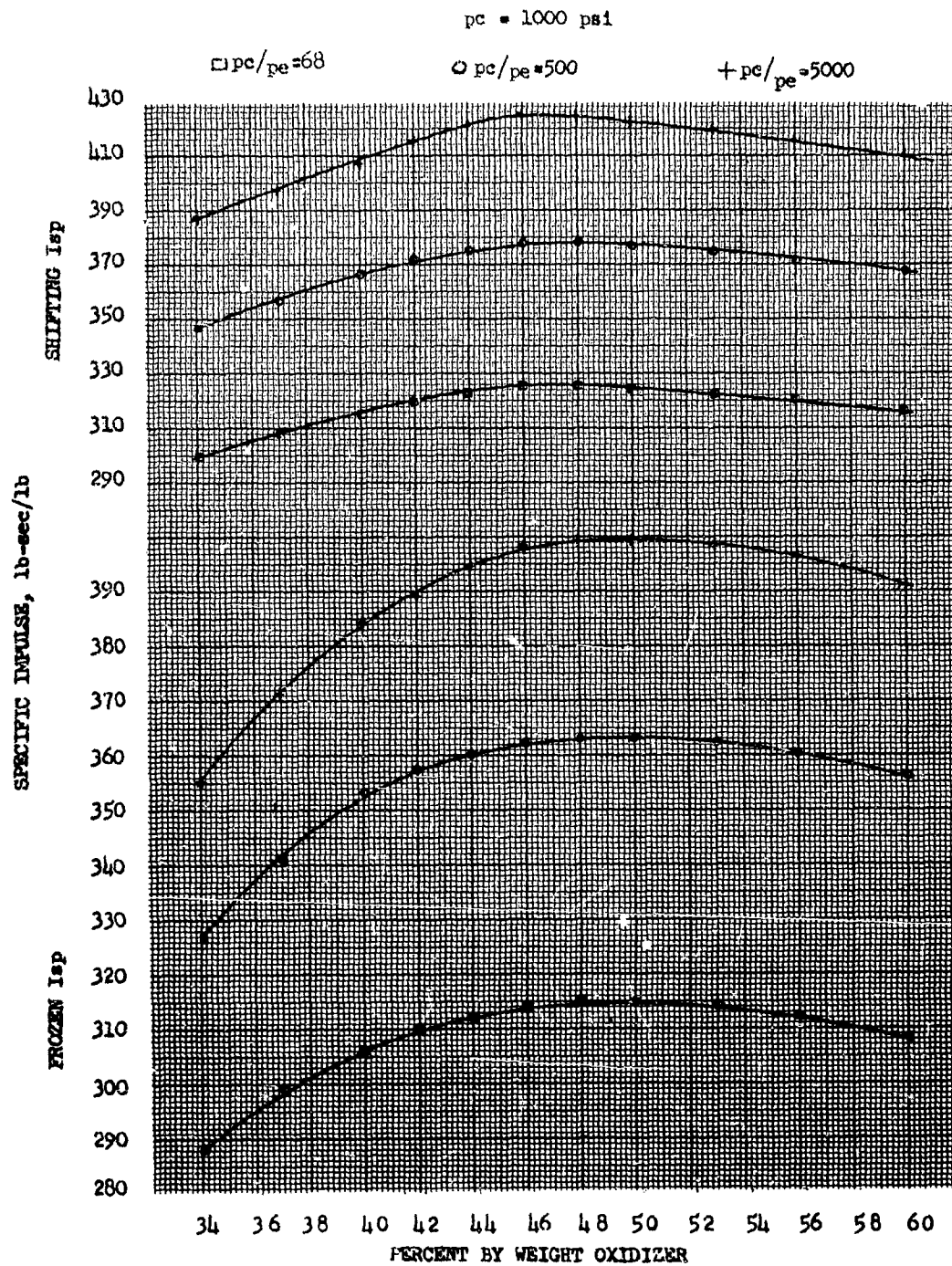
ALUMINUM HYDROXIDE - OXIDE DEPLETION OF PROPOXANES CURVES FIGURE 188



ALUMINUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 189



ALUMINUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 190



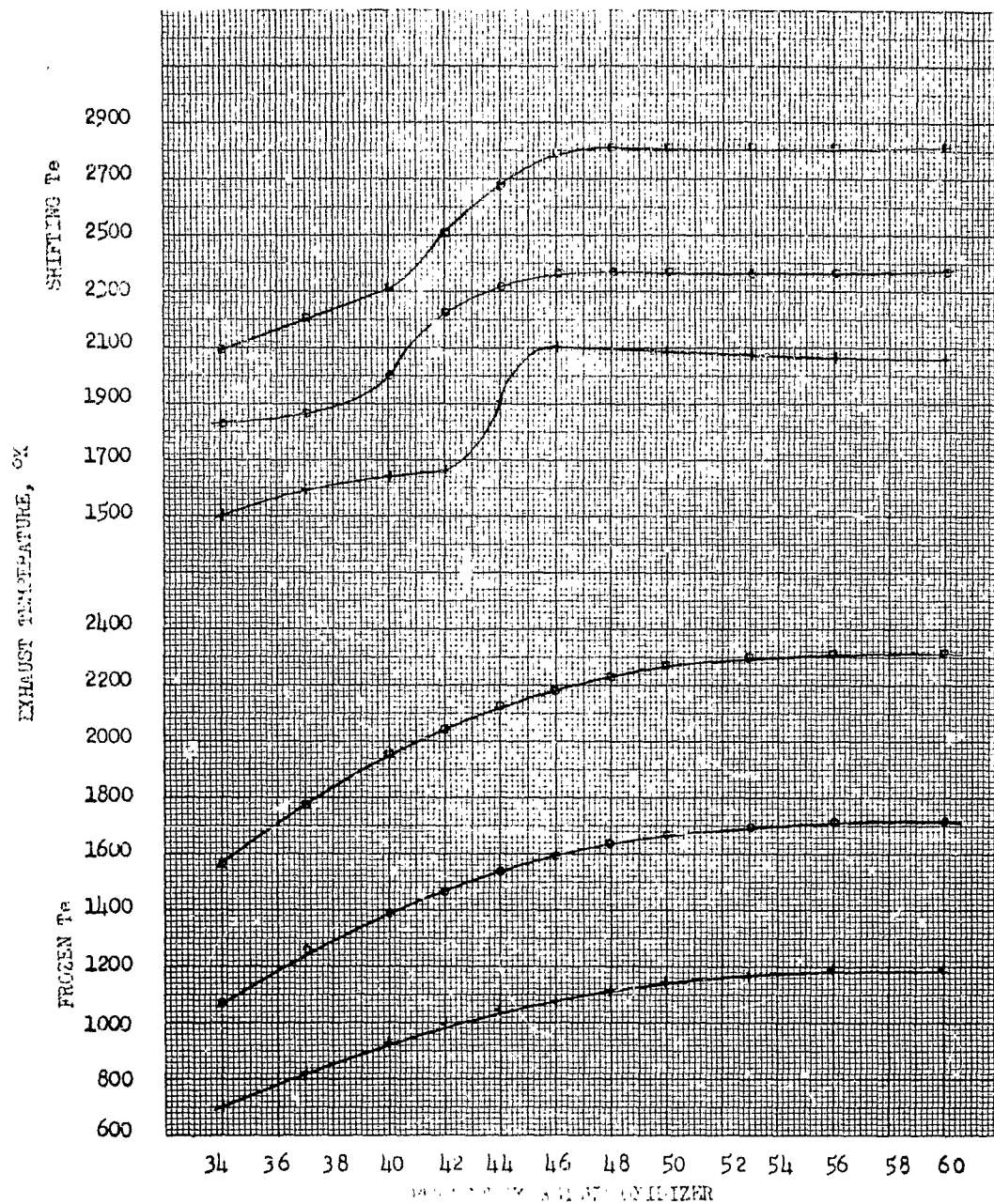
ALUMINUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 191

1000 10000

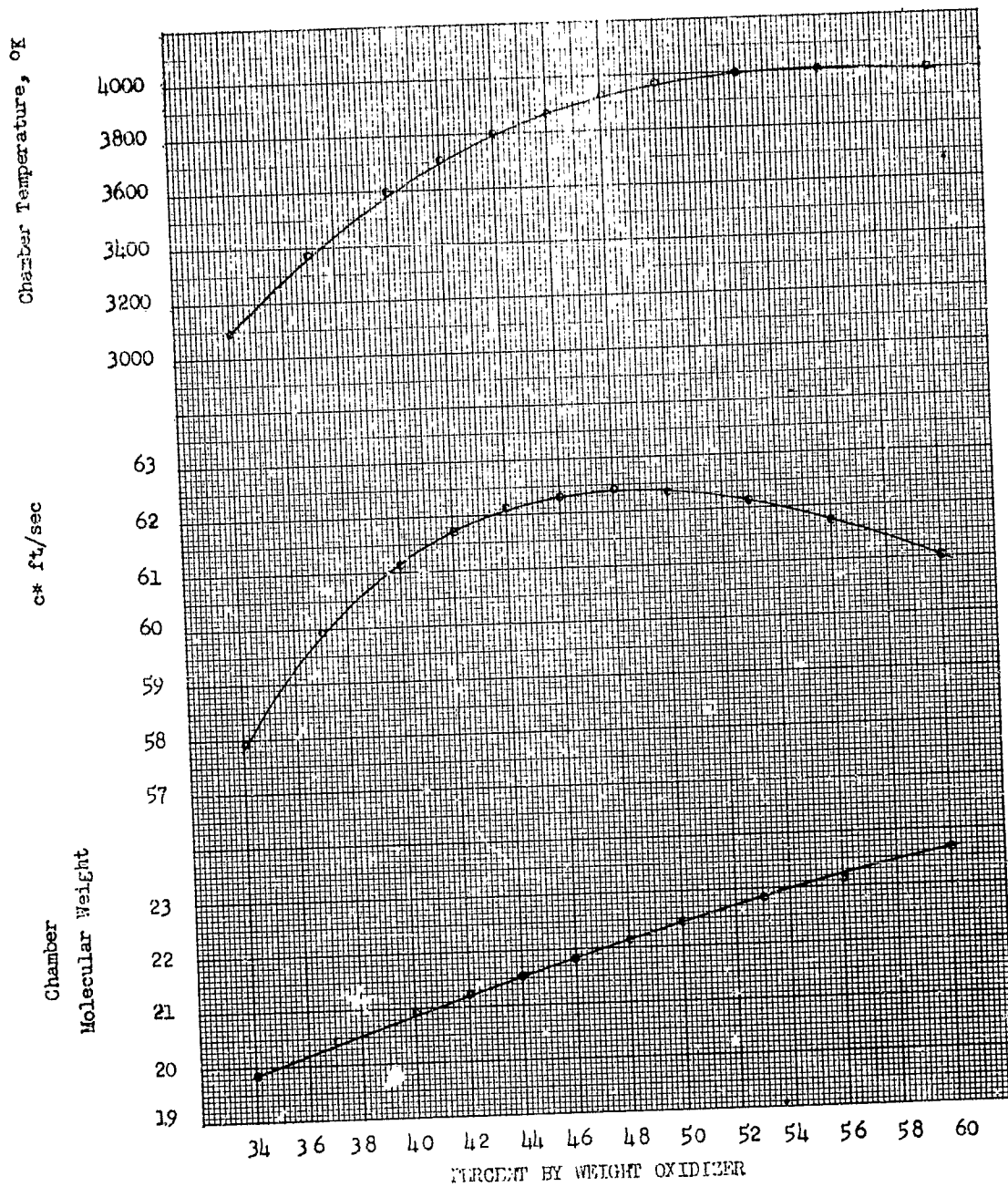
1000 10000

1000 10000

1000 10000



ALUMINUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 192



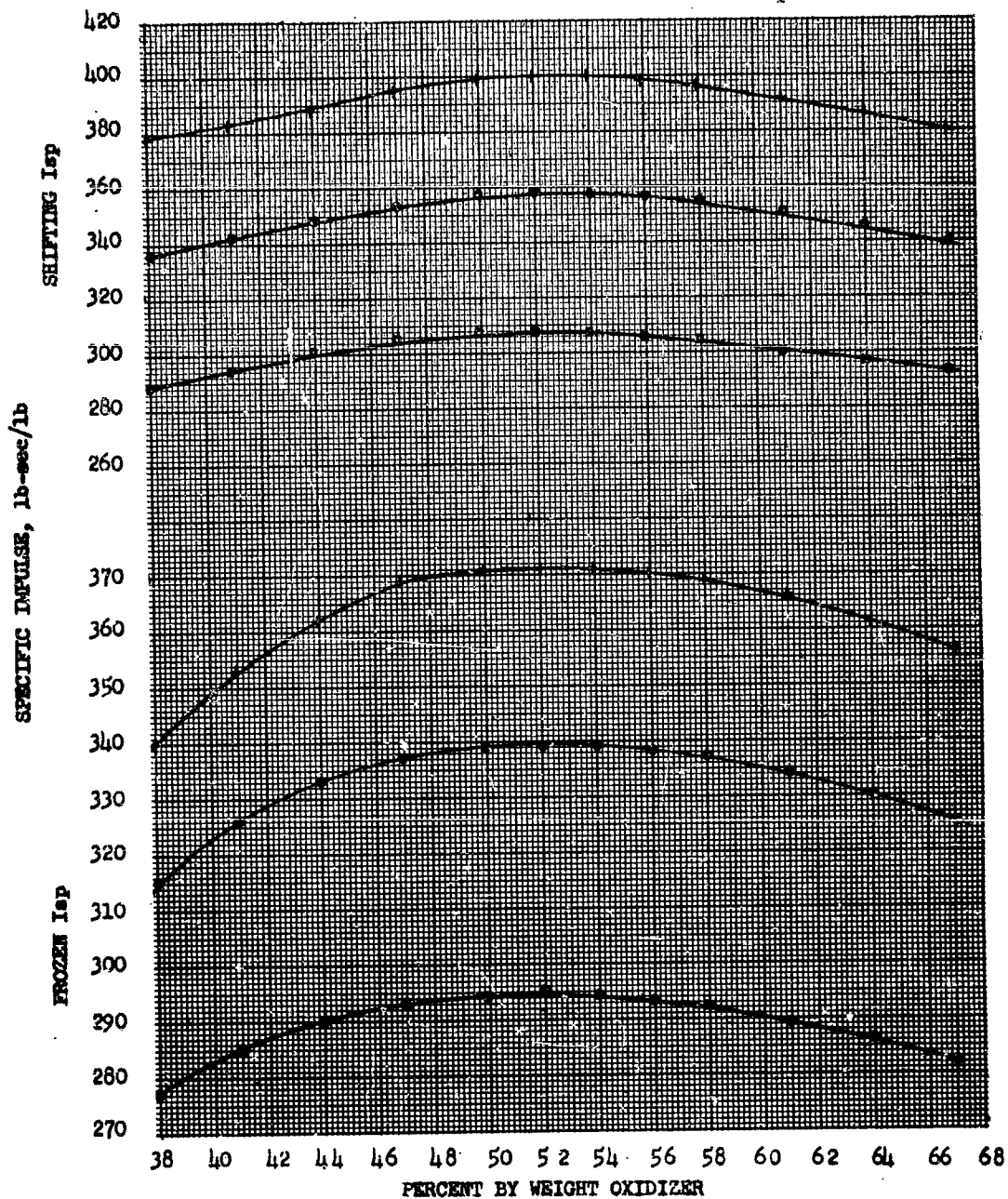
ALUMINUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 193

pc = 1000 psi

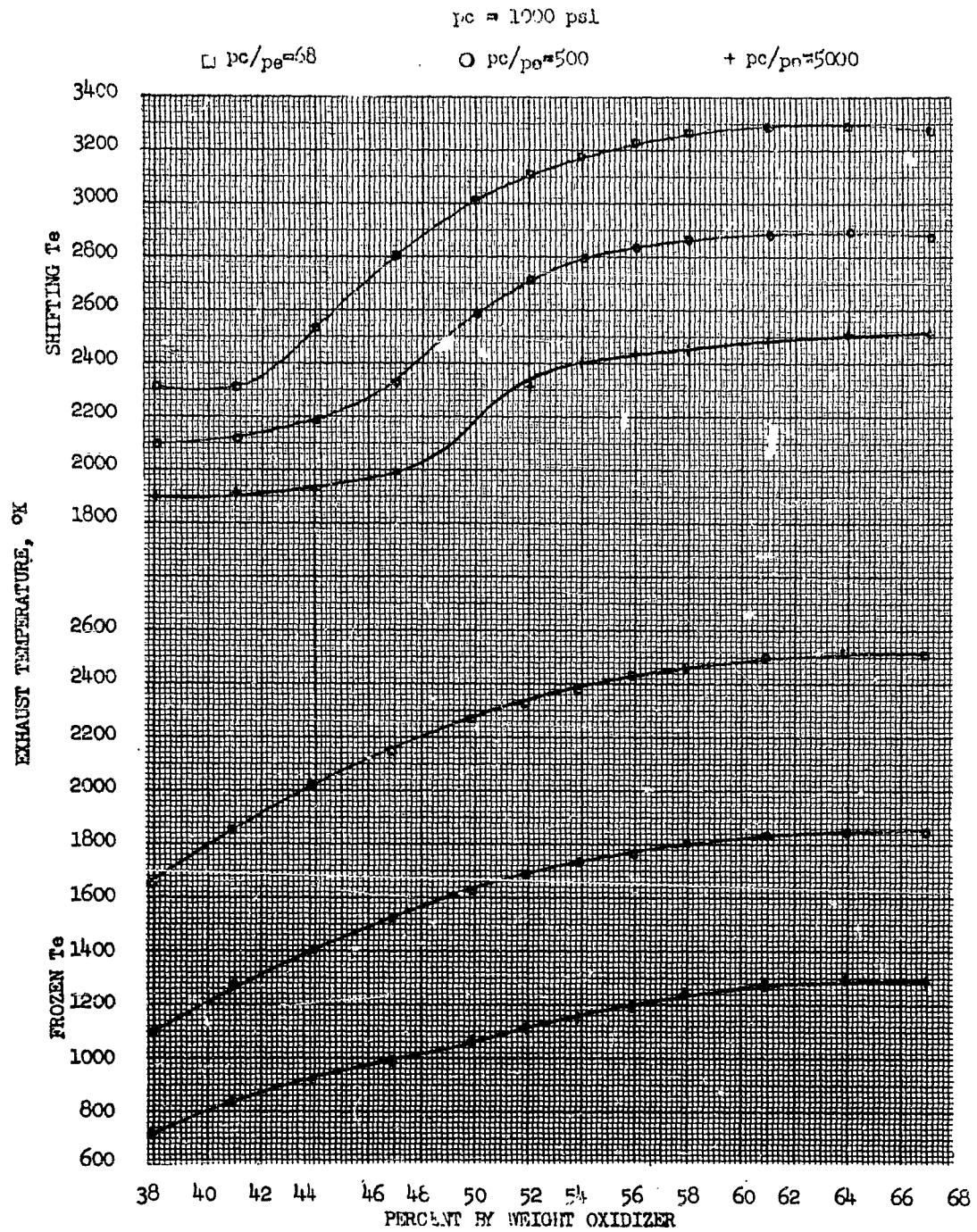
□ pc/pe = 68

○ pc/pe = 500

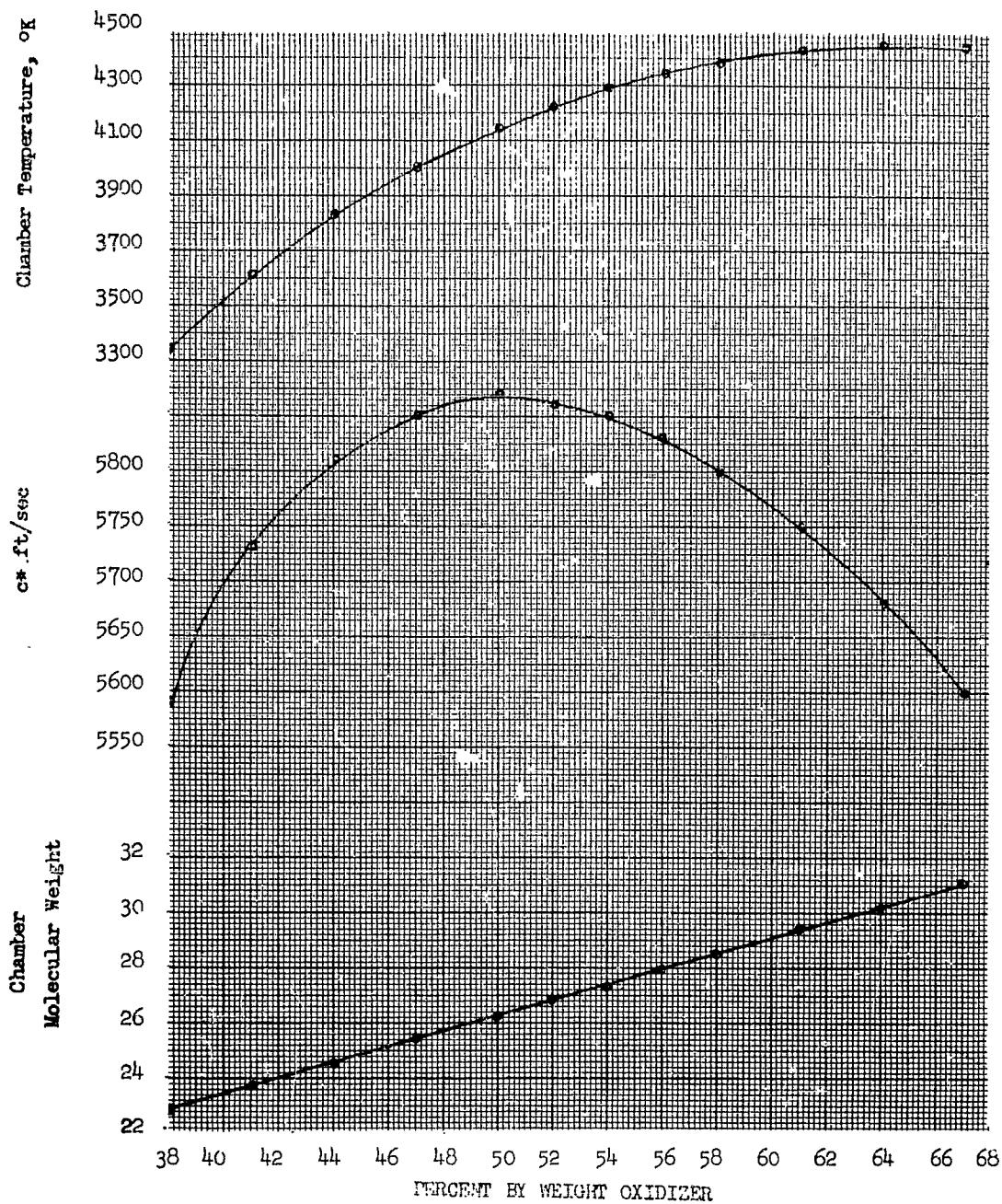
+ pc/pe = 5000



ALUMINUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 194



ALUMINUM HYDRIDE - NITROGEN TETROXIDE PERFORMANCE CURVES FIGURE 195



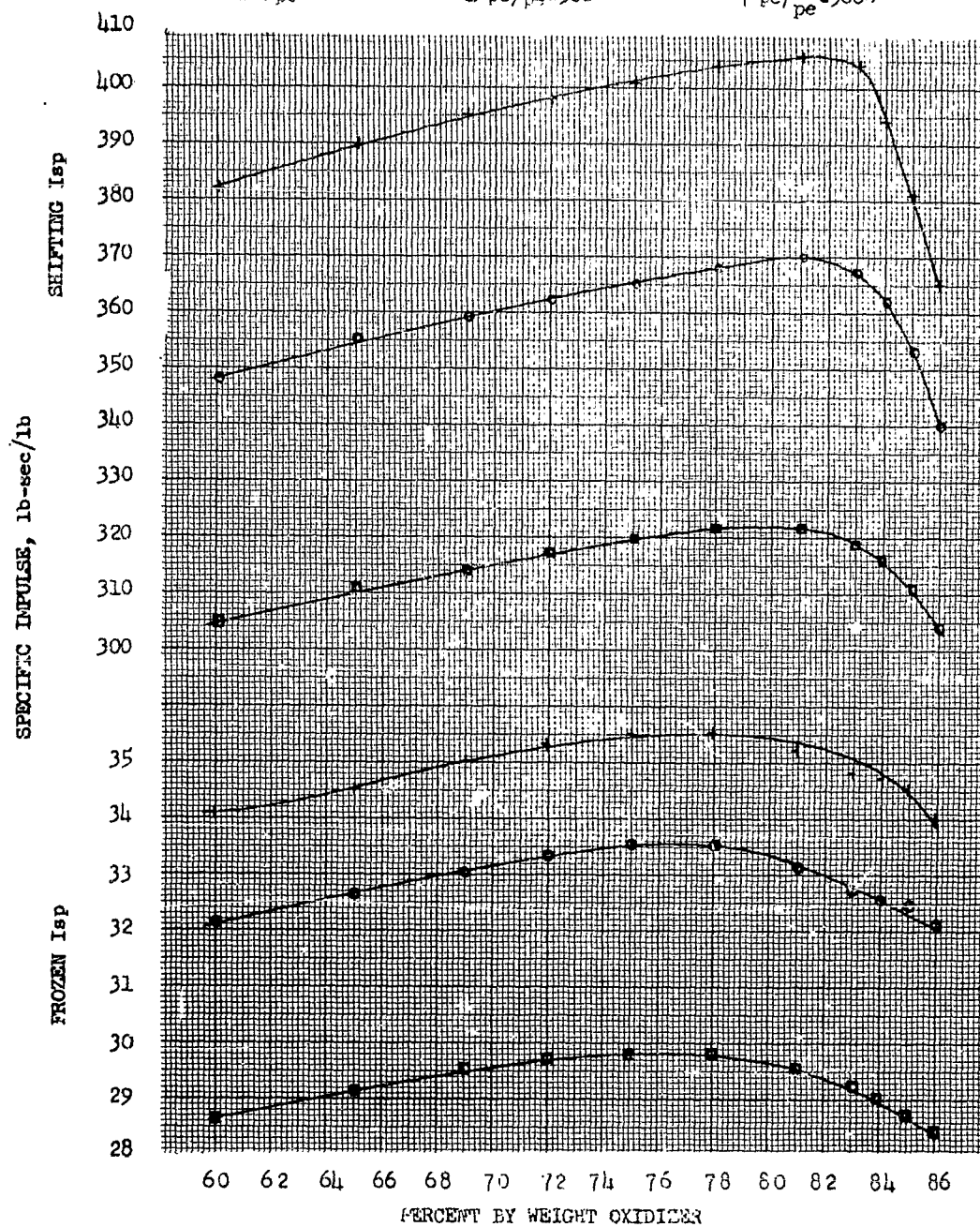
ALUMINUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 196

$p_c = 1000 \text{ psi}$

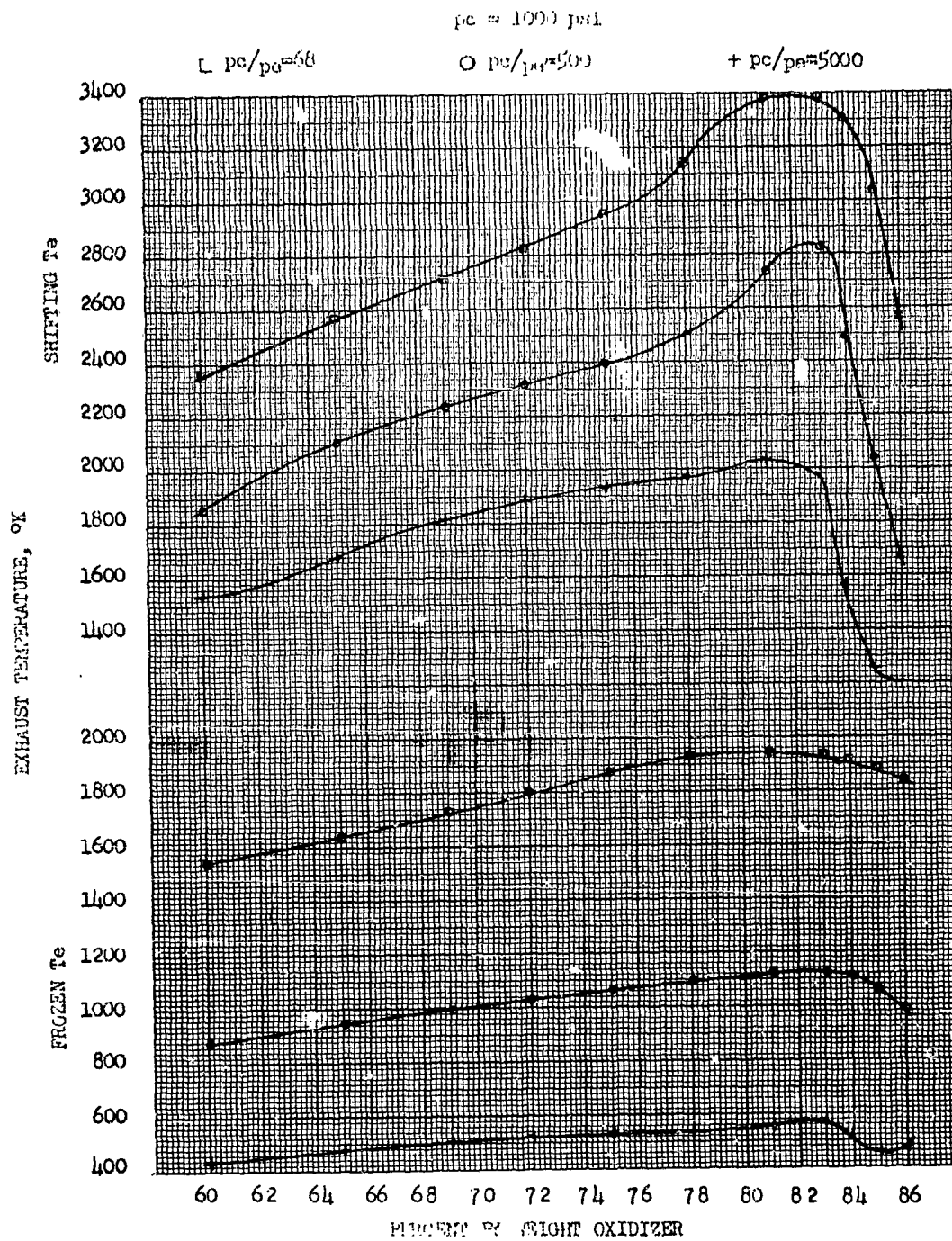
$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

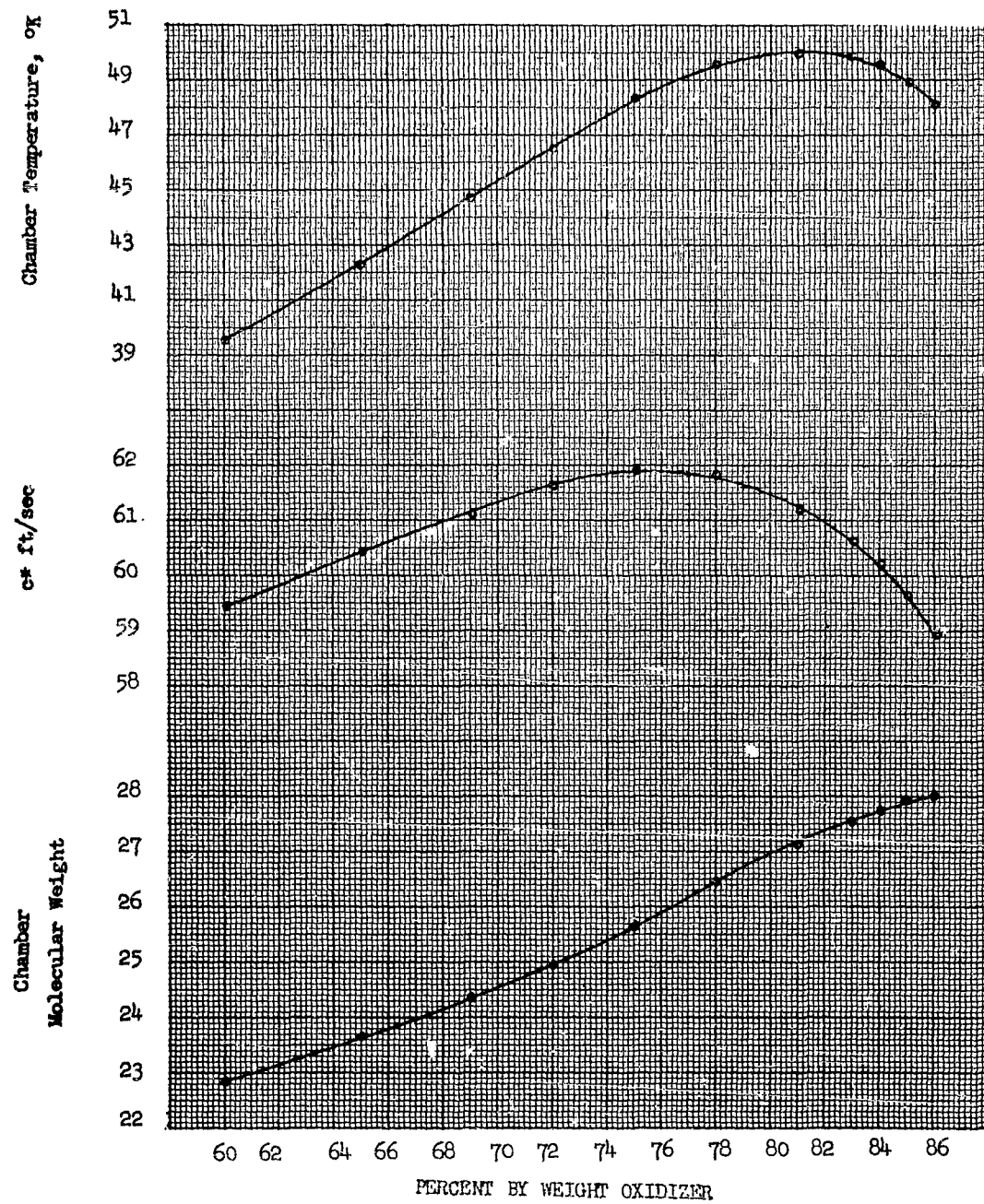
$+ p_c/p_e = 5000$



ALUMINUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 197



ALUMINUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 198



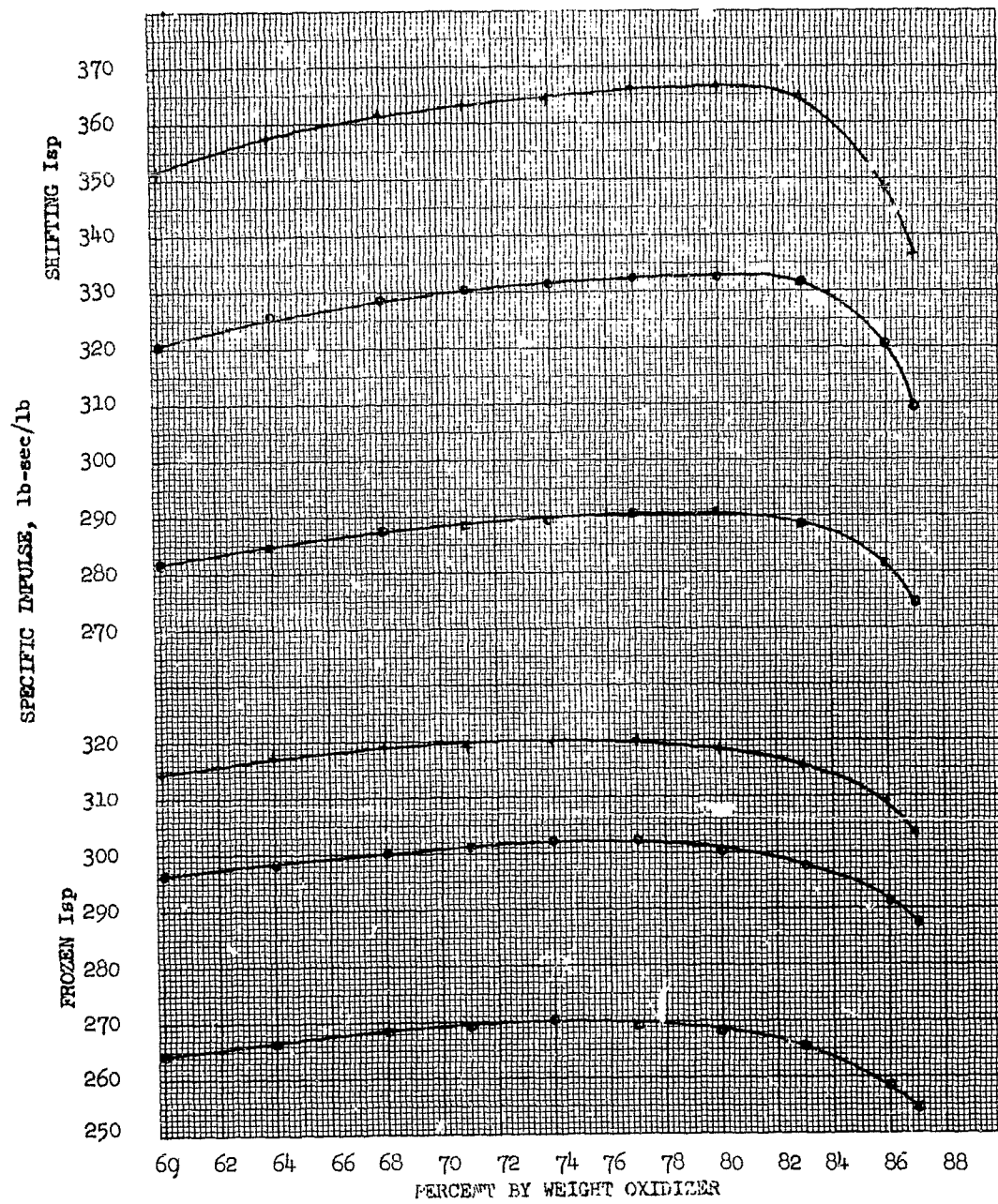
ALUMINUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 199

$p_c = 1000 \text{ psi}$

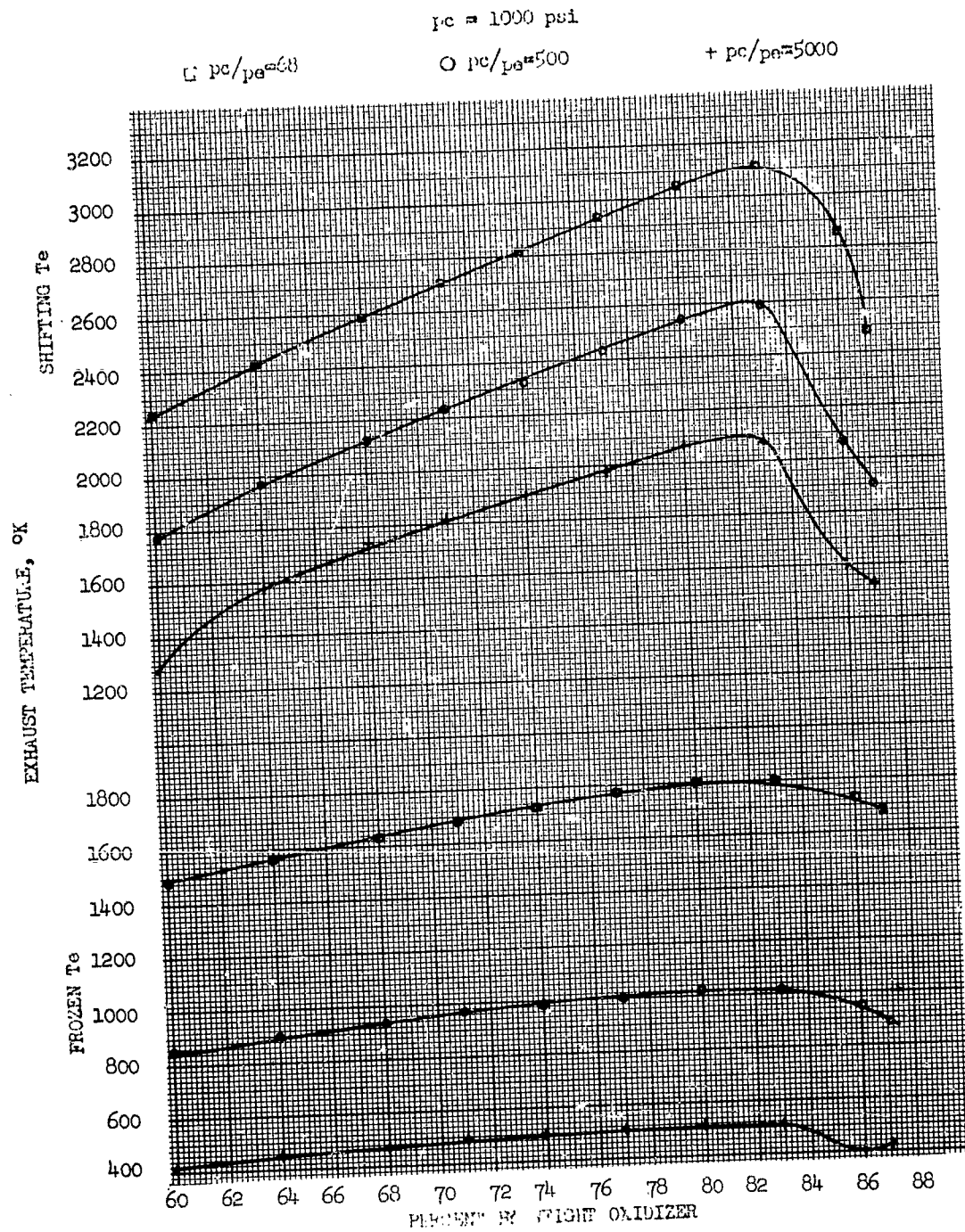
$\square p_c/p_e = 68$

$\circ p_c/p_e = 500$

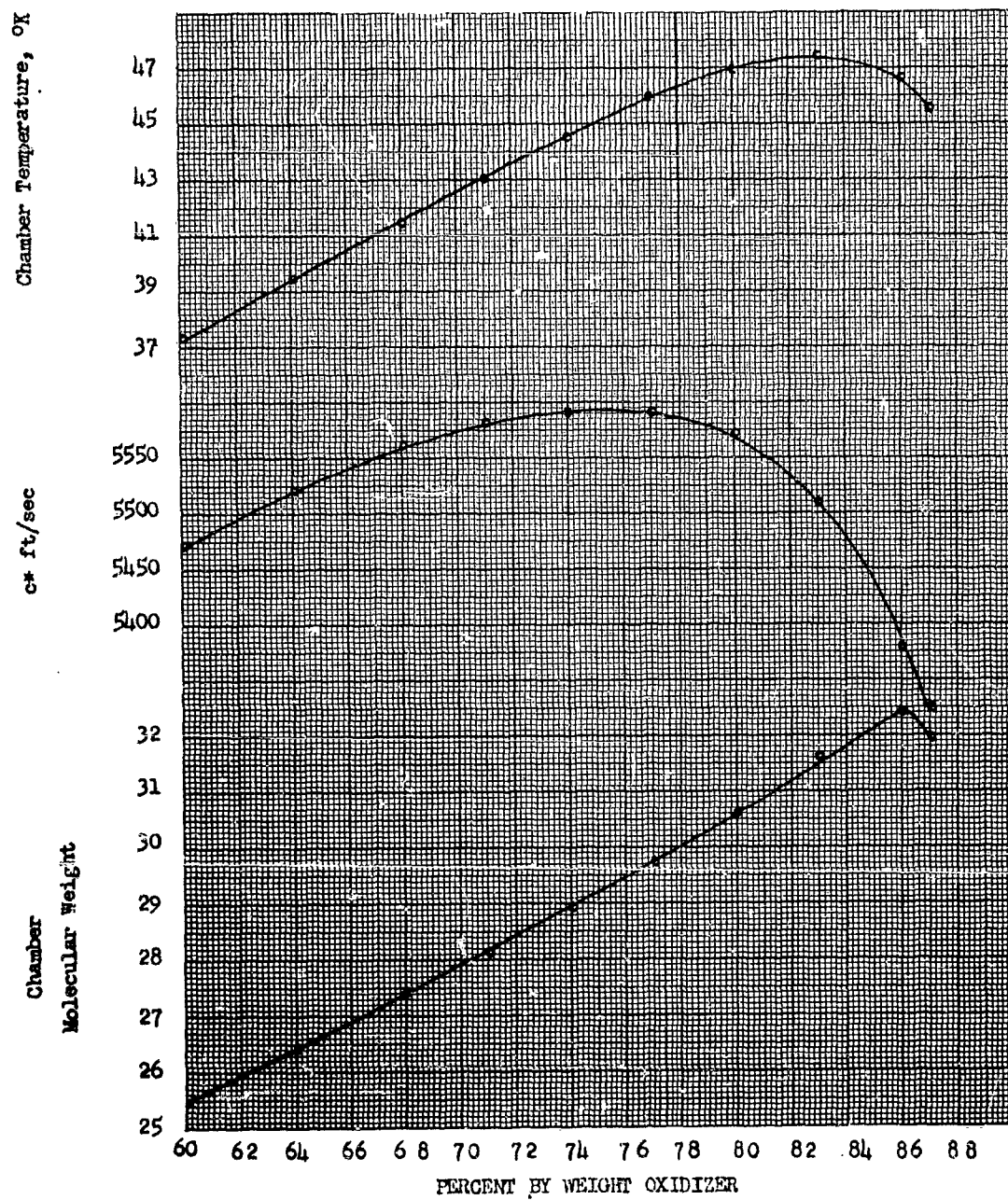
$+ p_c/p_e = 5000$



ALUMINUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 200

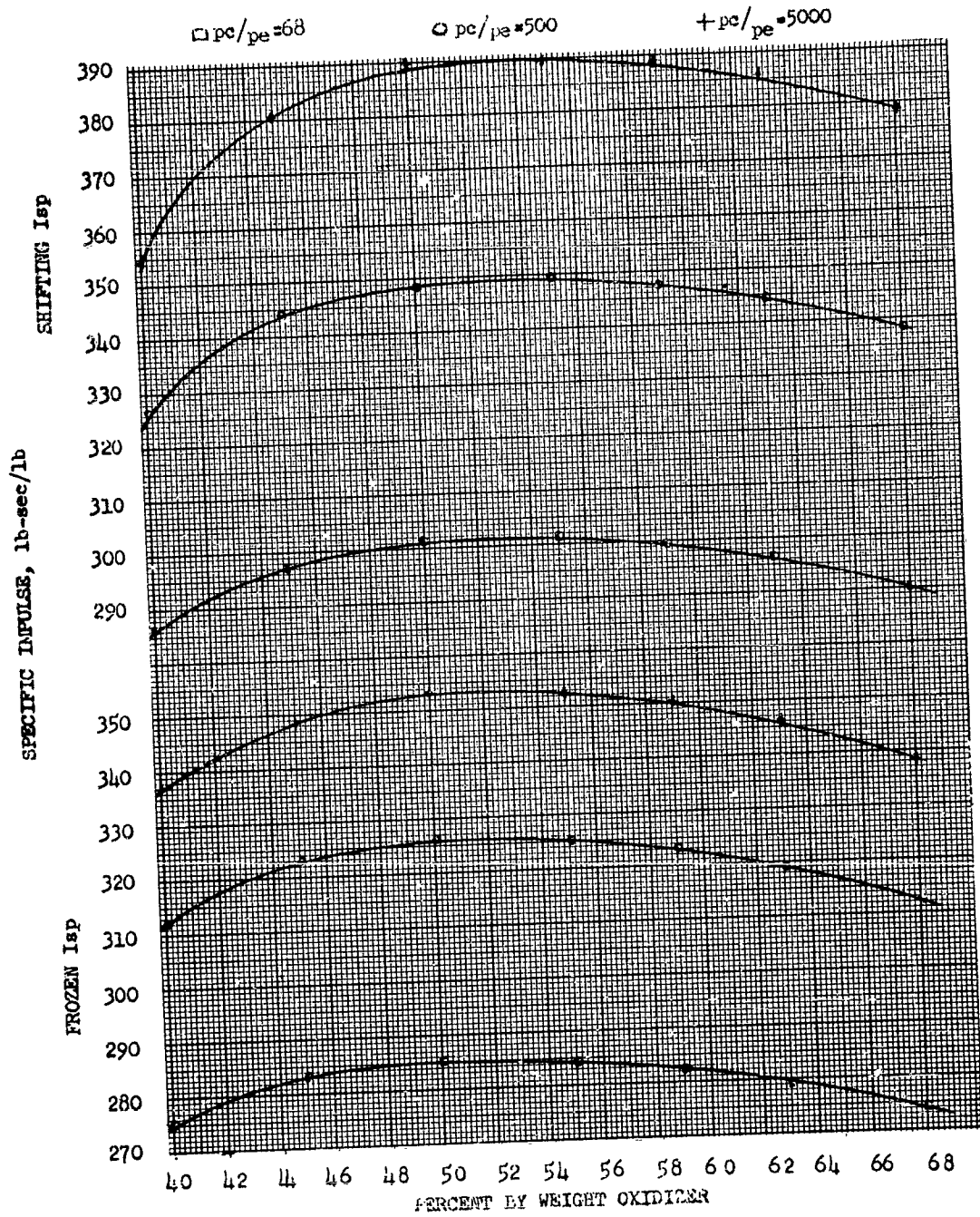


ALUMINUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 201



ALUMINUM HYDRIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 202

pc = 1000 psi



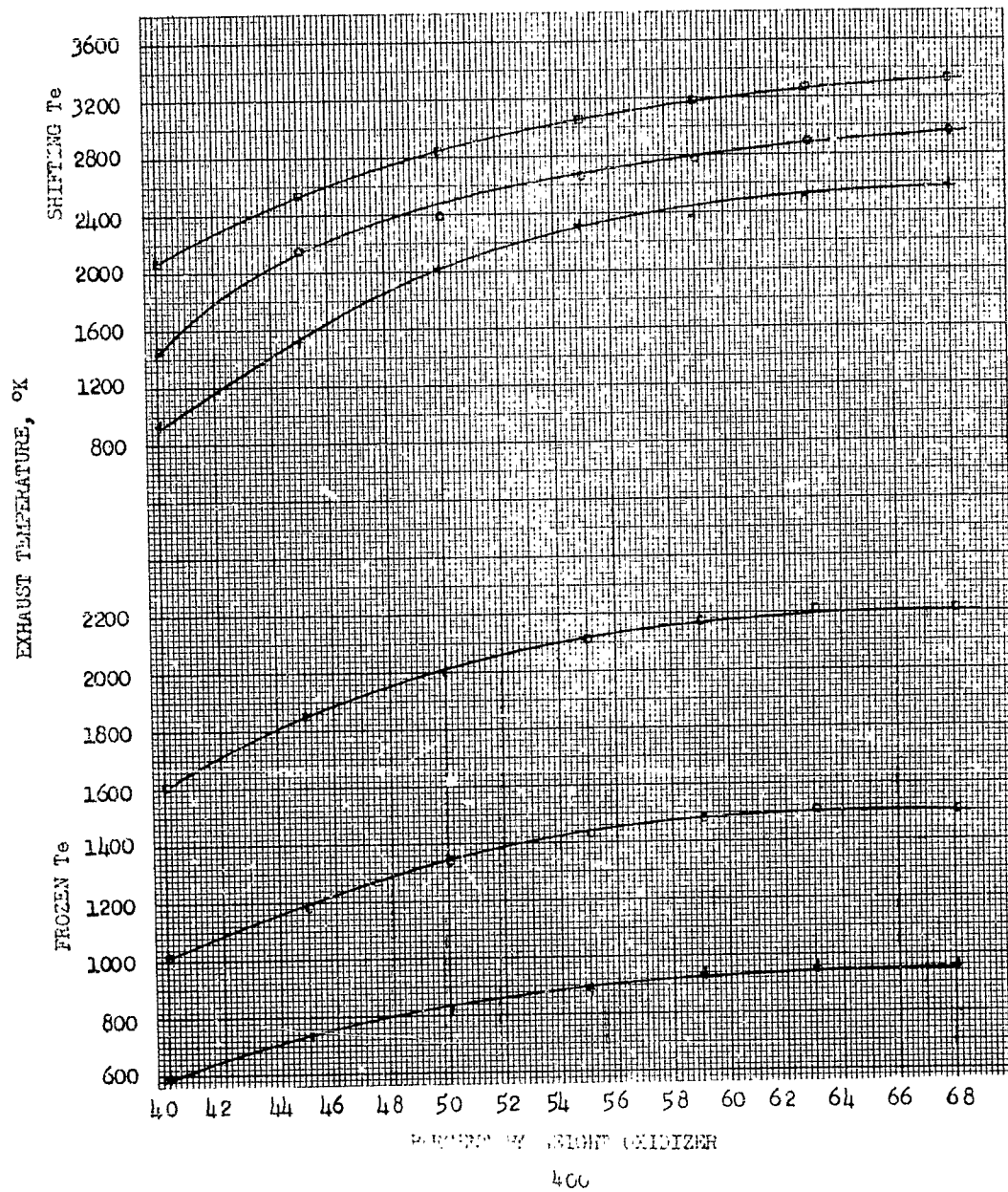
ALUMINUM HYDRIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 203

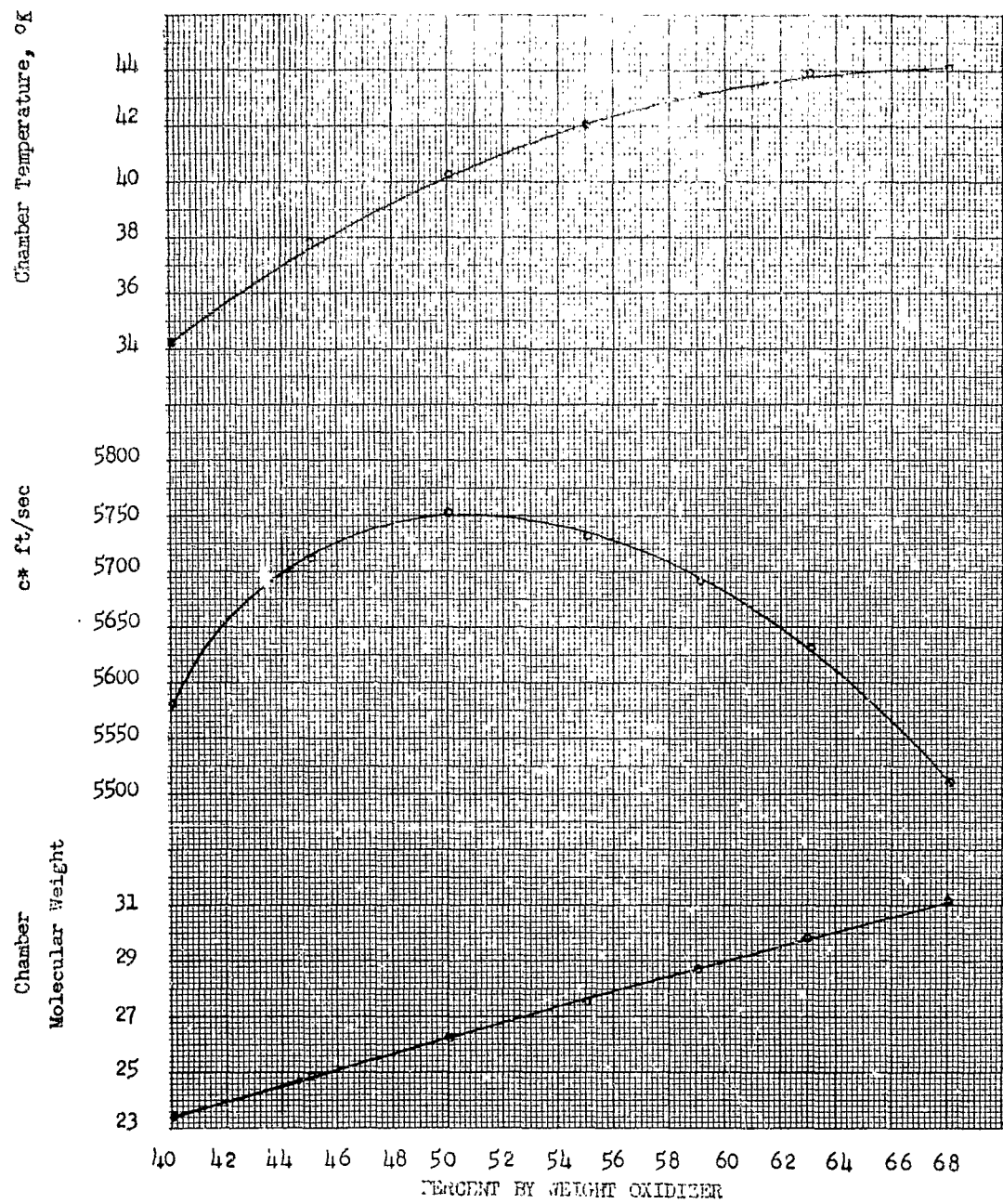
1000000

1000000

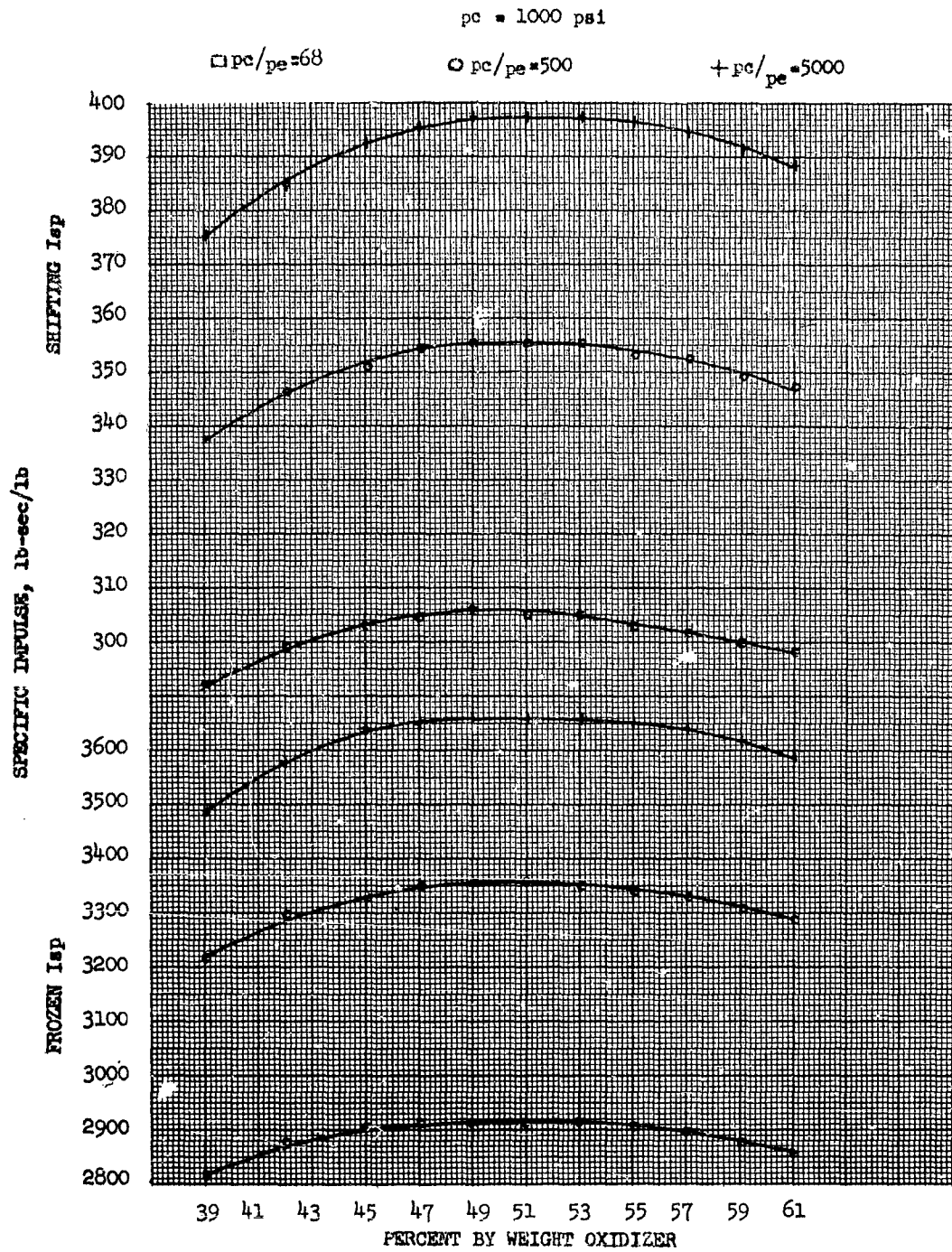
1000000

1000000

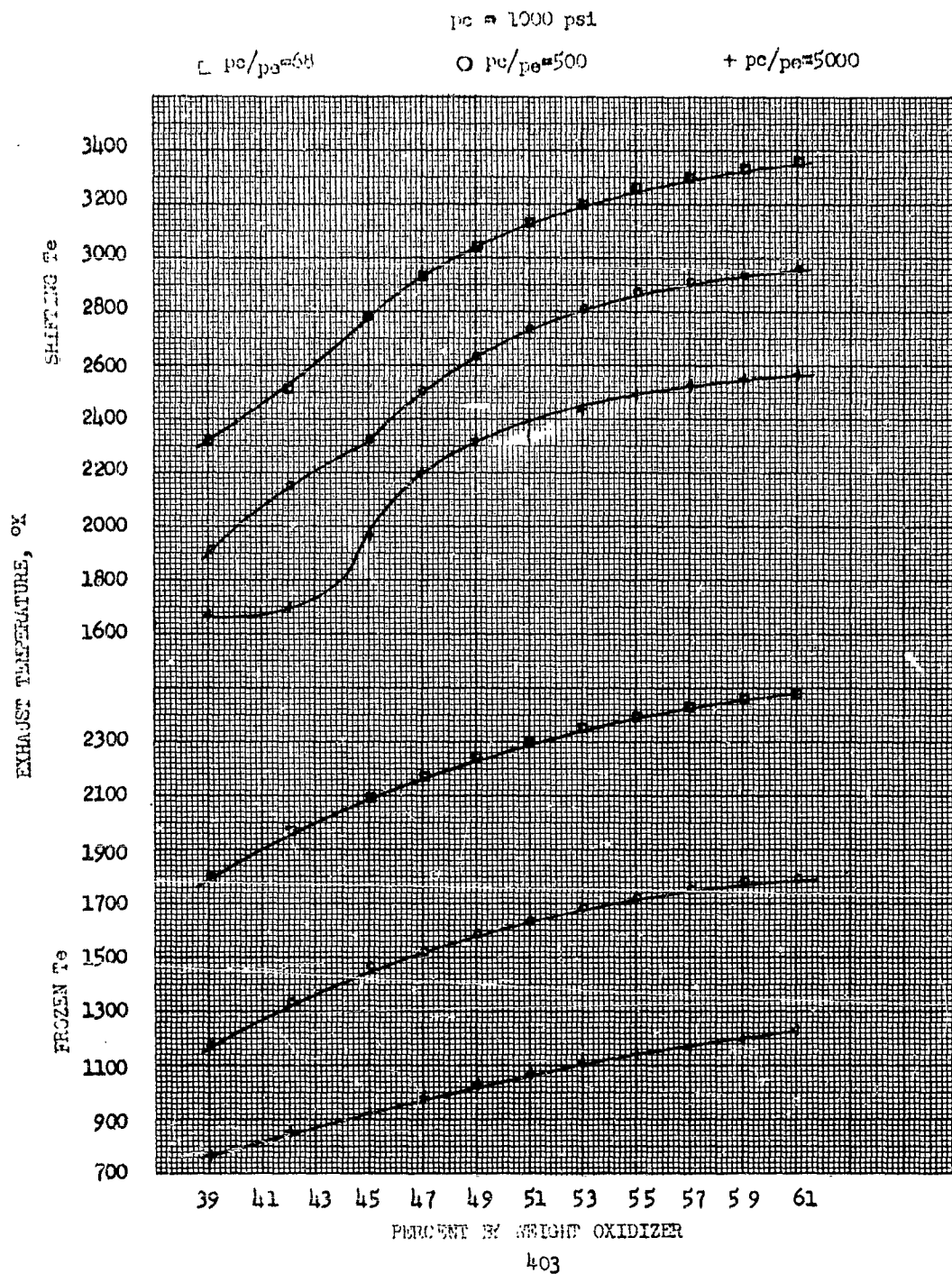




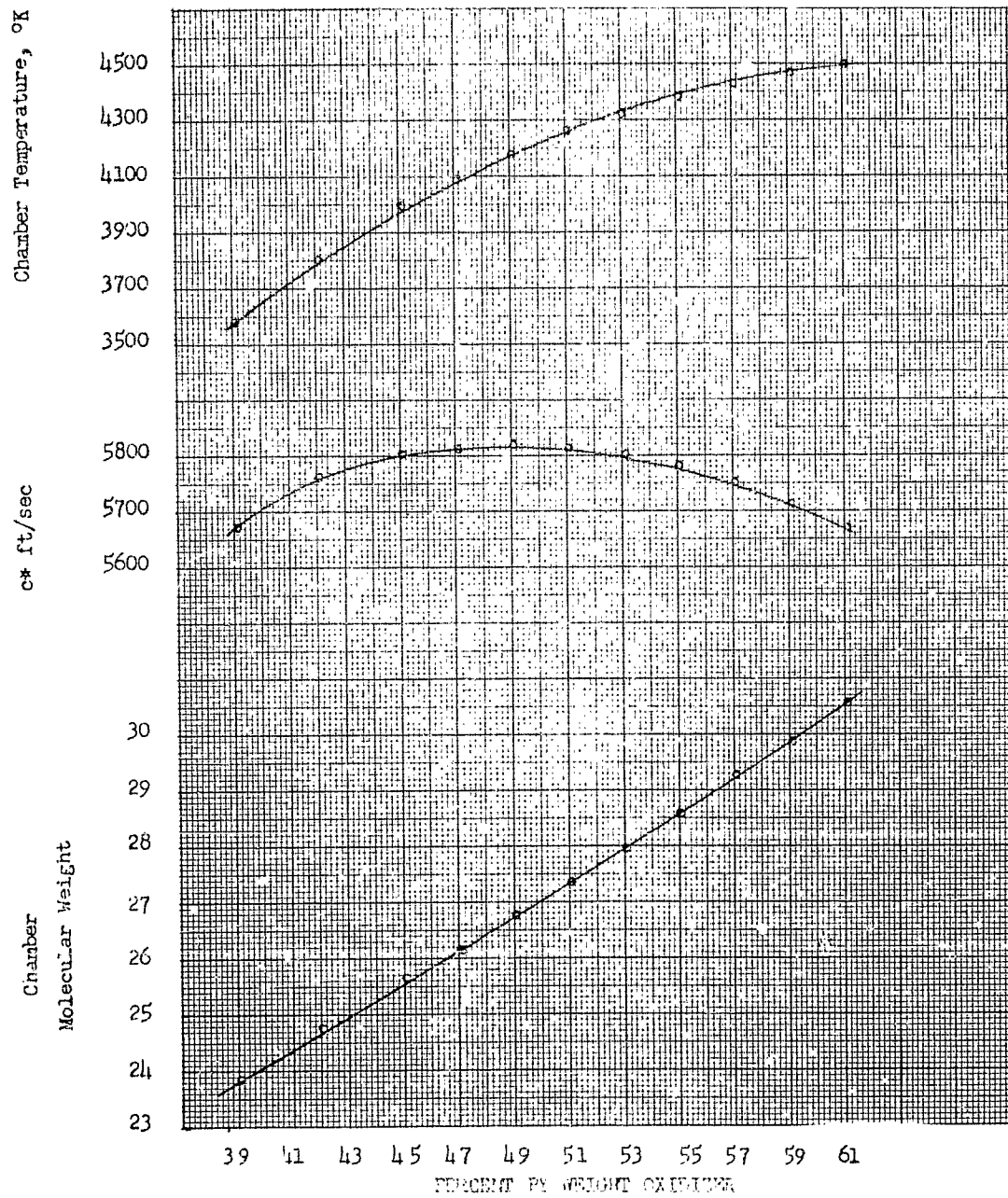
ALUMINUM HYDRIDE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 205



ALUMINUM HYDRIDE - NITRONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 206



ALUMINUM HYDROXIDE - MONOCHLOROPHOSPHATE PERFORMANCE SURVEY FIGURE 207



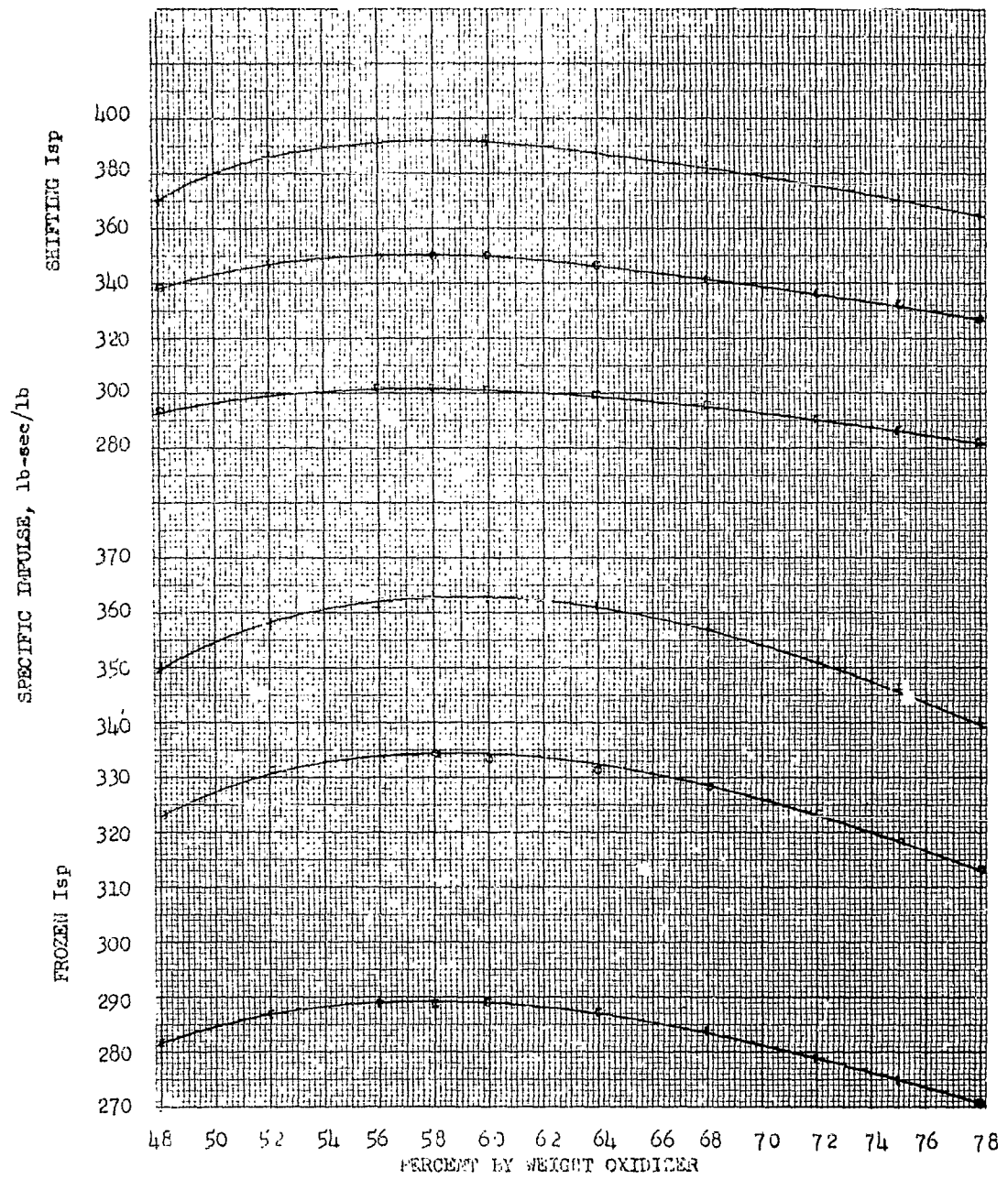
ALUMINUM HYDRIDE - ALUMINUM PERCHLORATE PERFORMANCE CURVES FIGURE 208

PERCENT BY WEIGHT OXIDIZER

$\frac{I_{sp}}{p_c} = 200$

$\frac{I_{sp}}{p_c} = 500$

$\frac{I_{sp}}{p_c} = 5000$



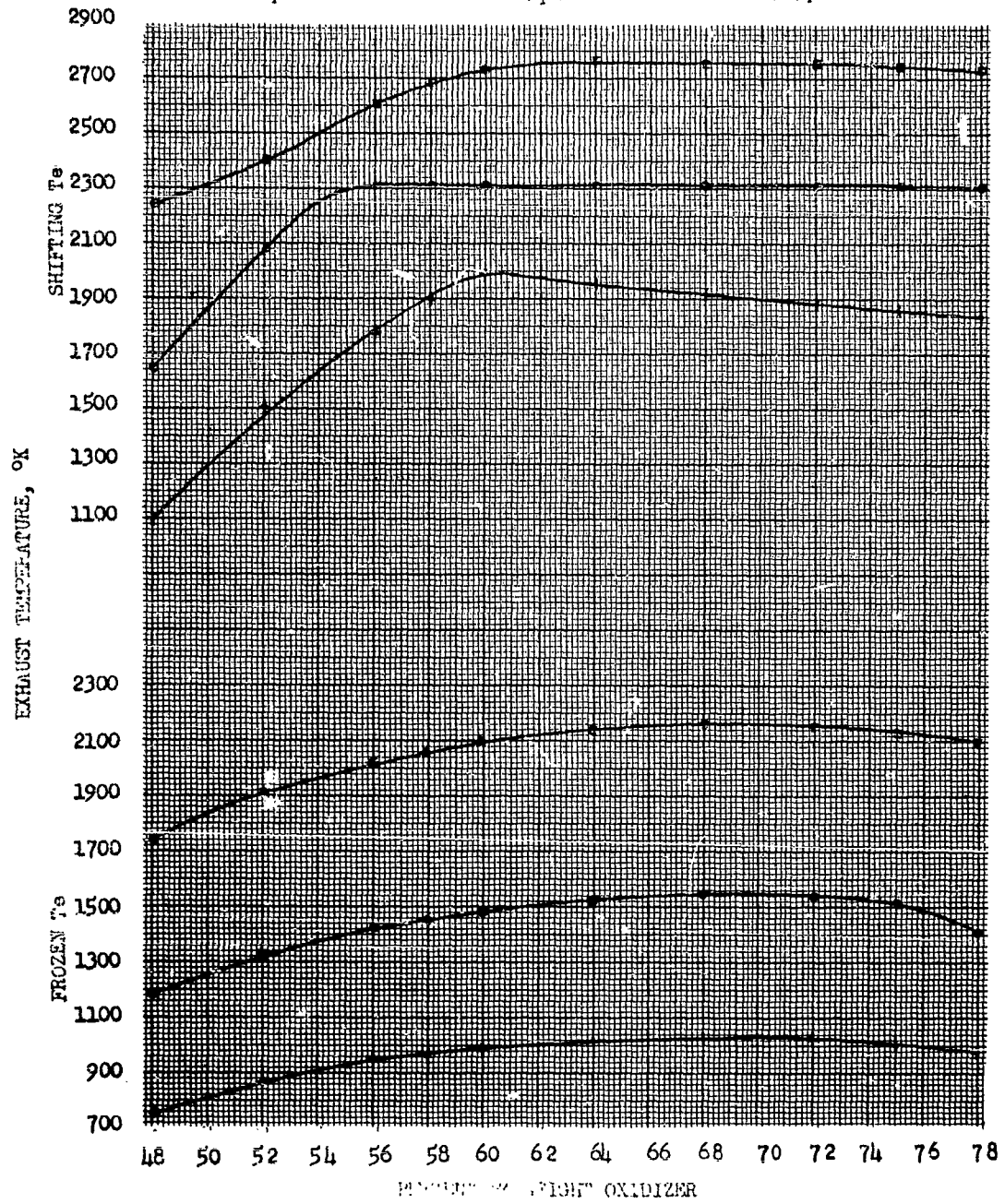
ALUMINUM HYDRIDE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 209

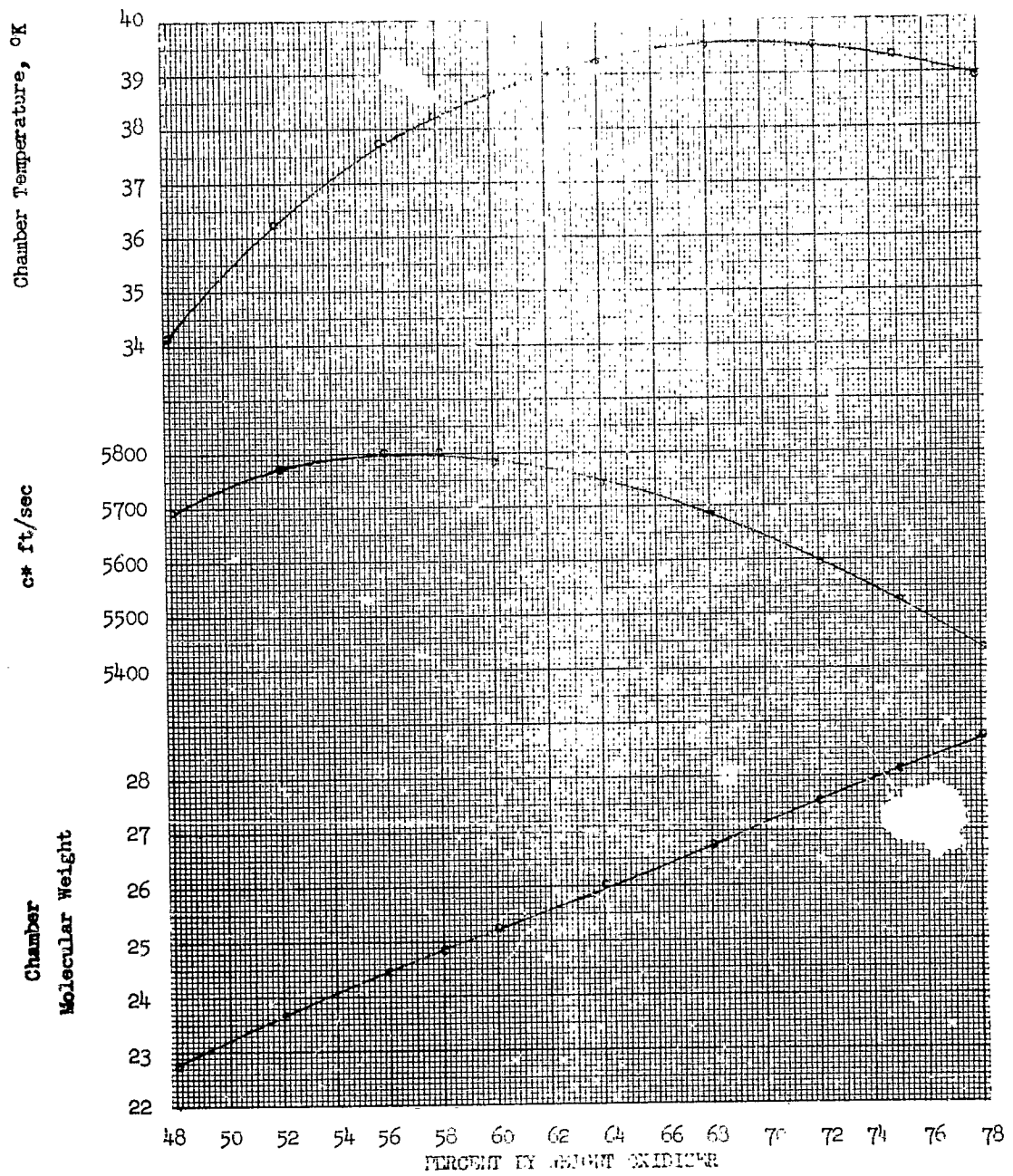
$p_c = 1000 \text{ psi}$

$\square p_c/p_a = 68$

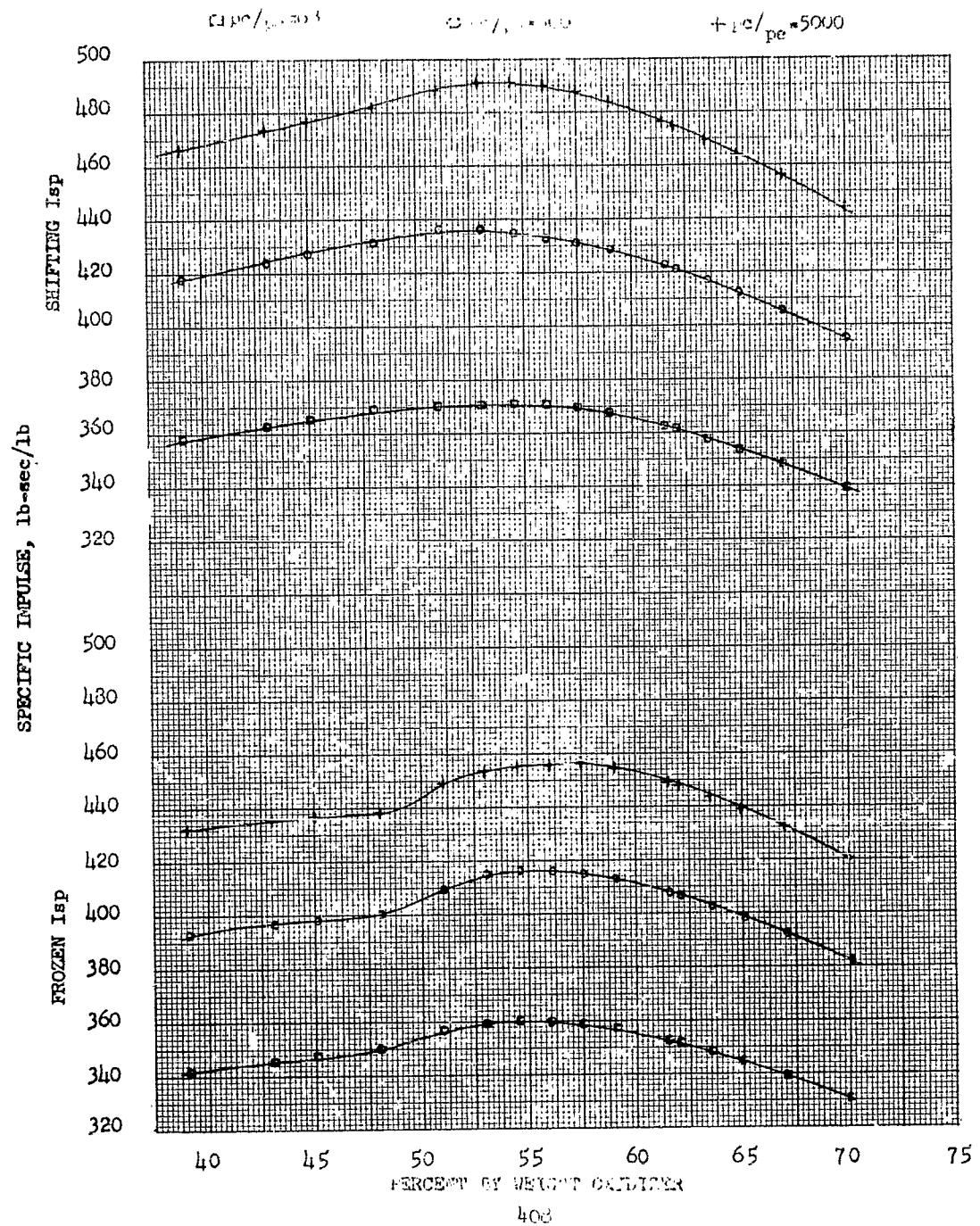
$\circ p_c/p_a = 500$

$+ p_c/p_a = 5000$

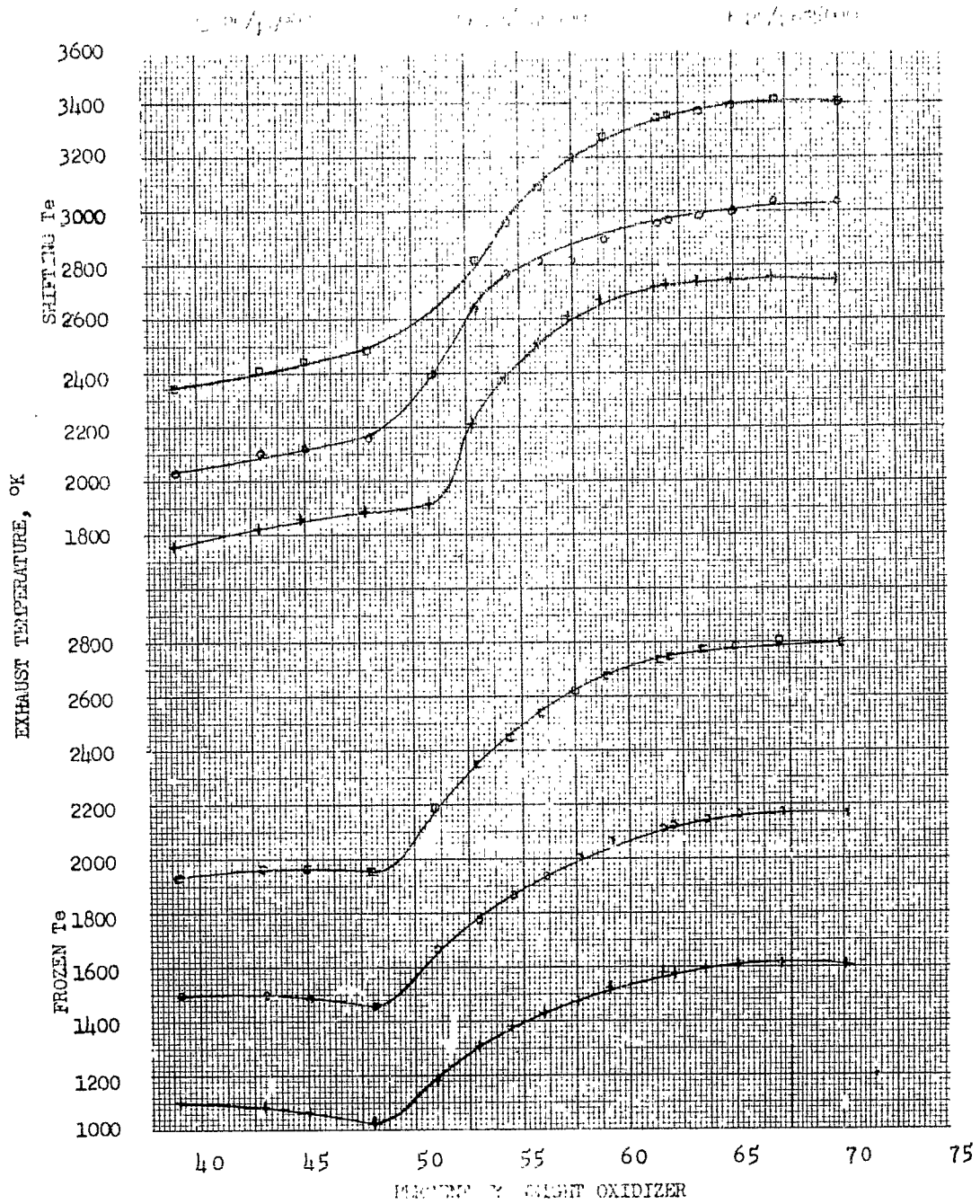




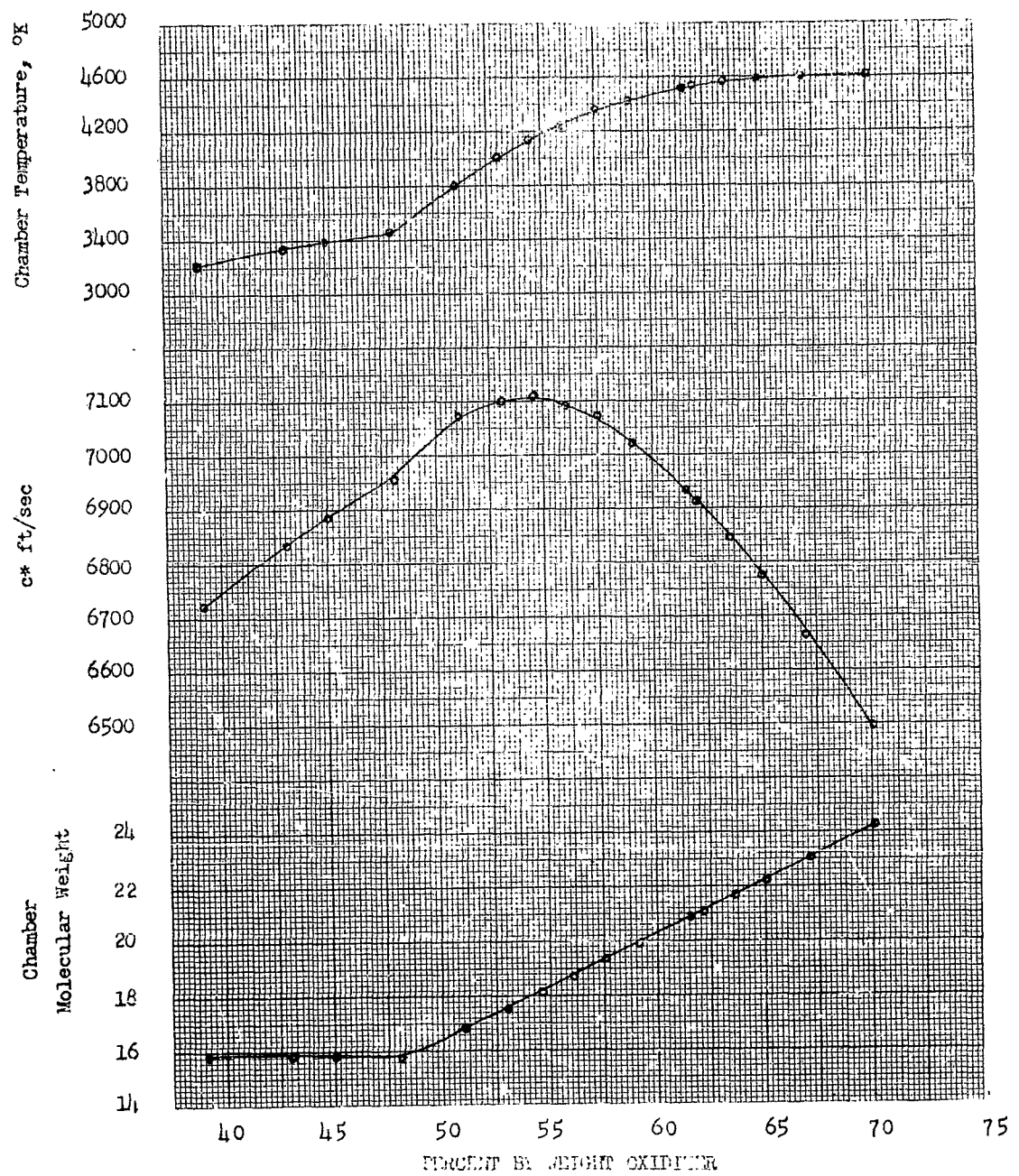
BERYLLIUM HYDRIDE - LIQUID OX GEN PERFORMANCE CURVES FIGURE 211



BERYLLIUM NITRIDE - FROZEN TE



BERYLLIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 213



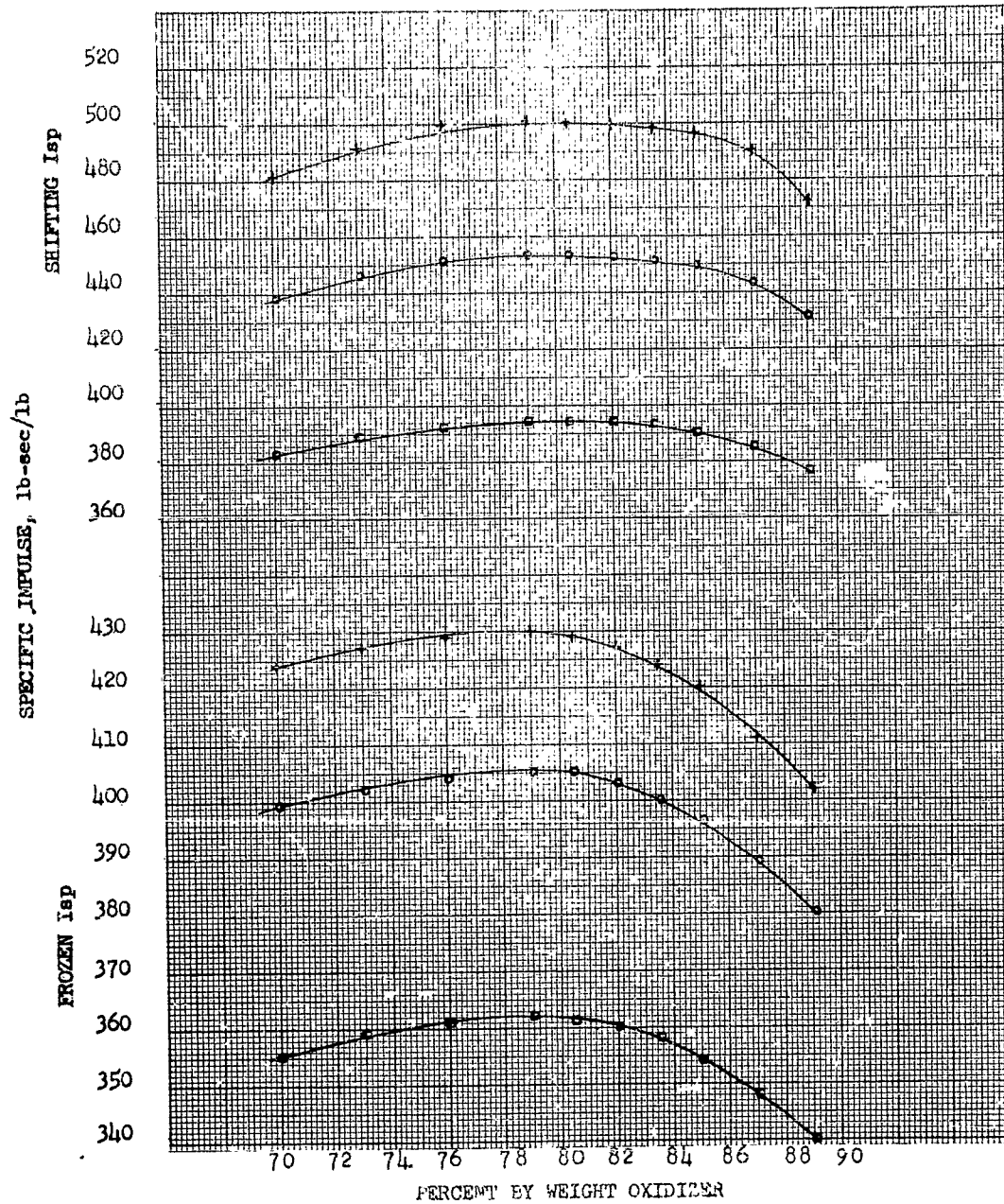
BERYLLIUM HYDRIDE - LIQUID FLOODED PERFORMANCE CURVES FIGURE 211

10000 psi

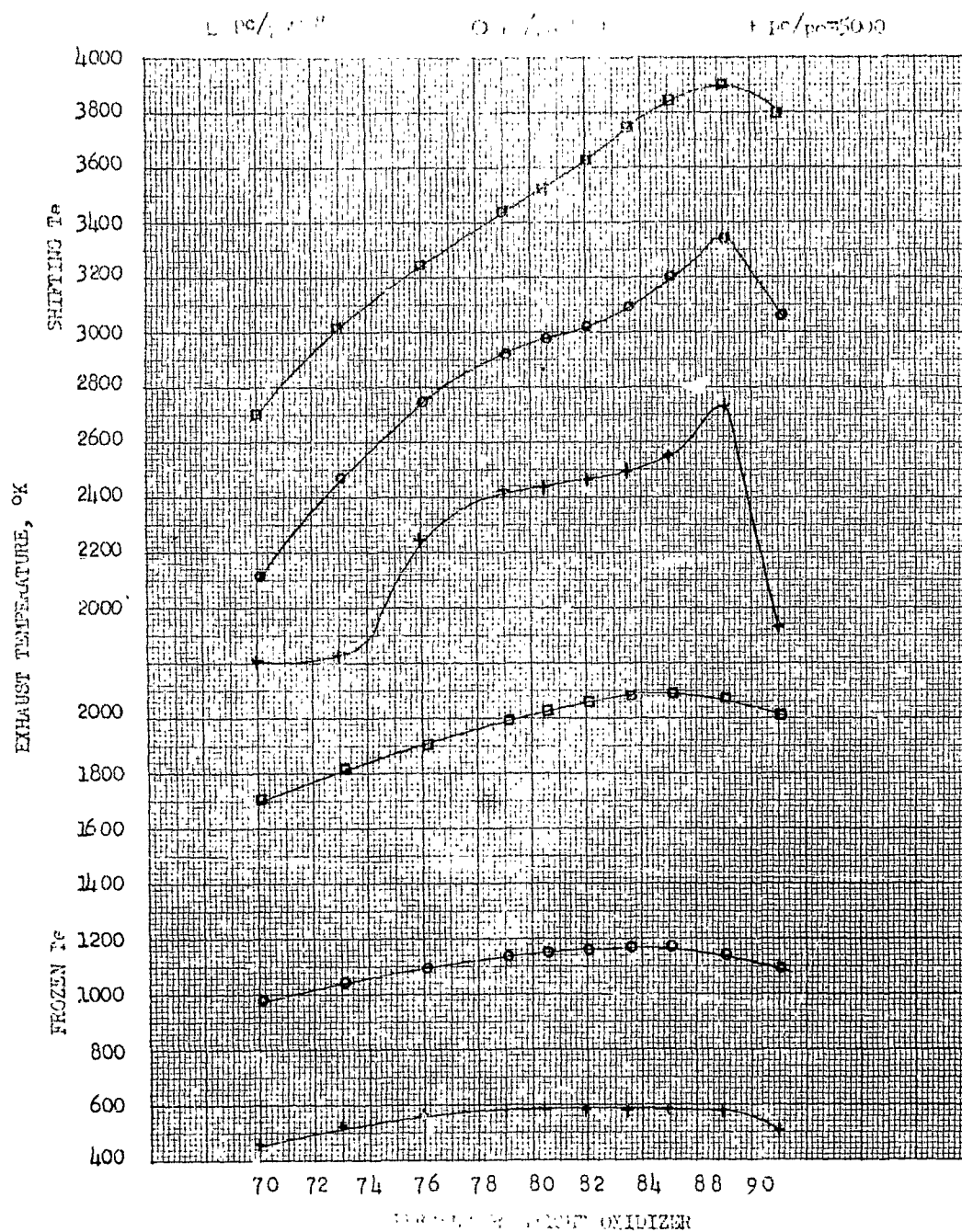
□ $p_c/p_e = 100$

○ $p_c/p_e = 500$

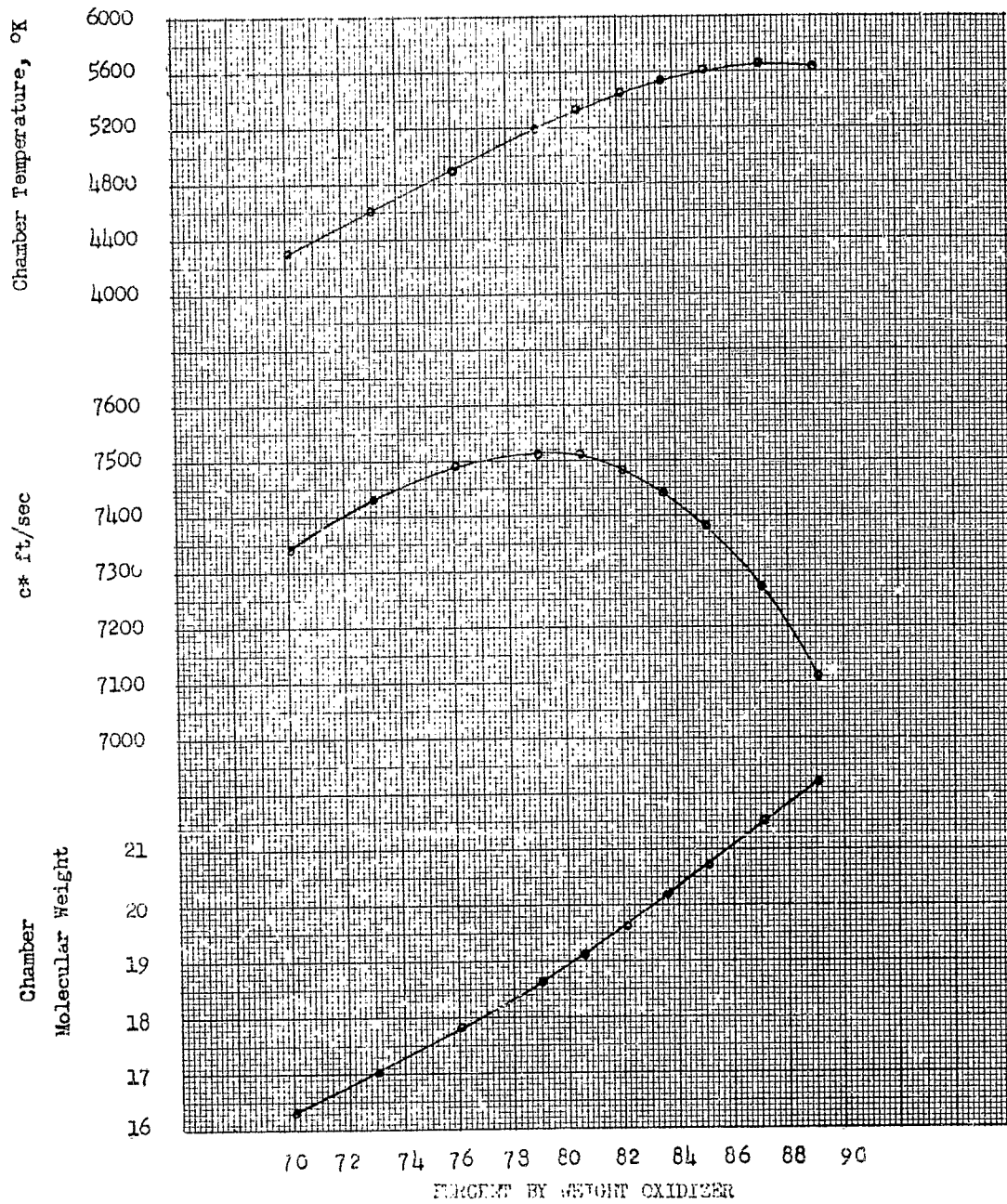
+ $p_c/p_e = 5000$



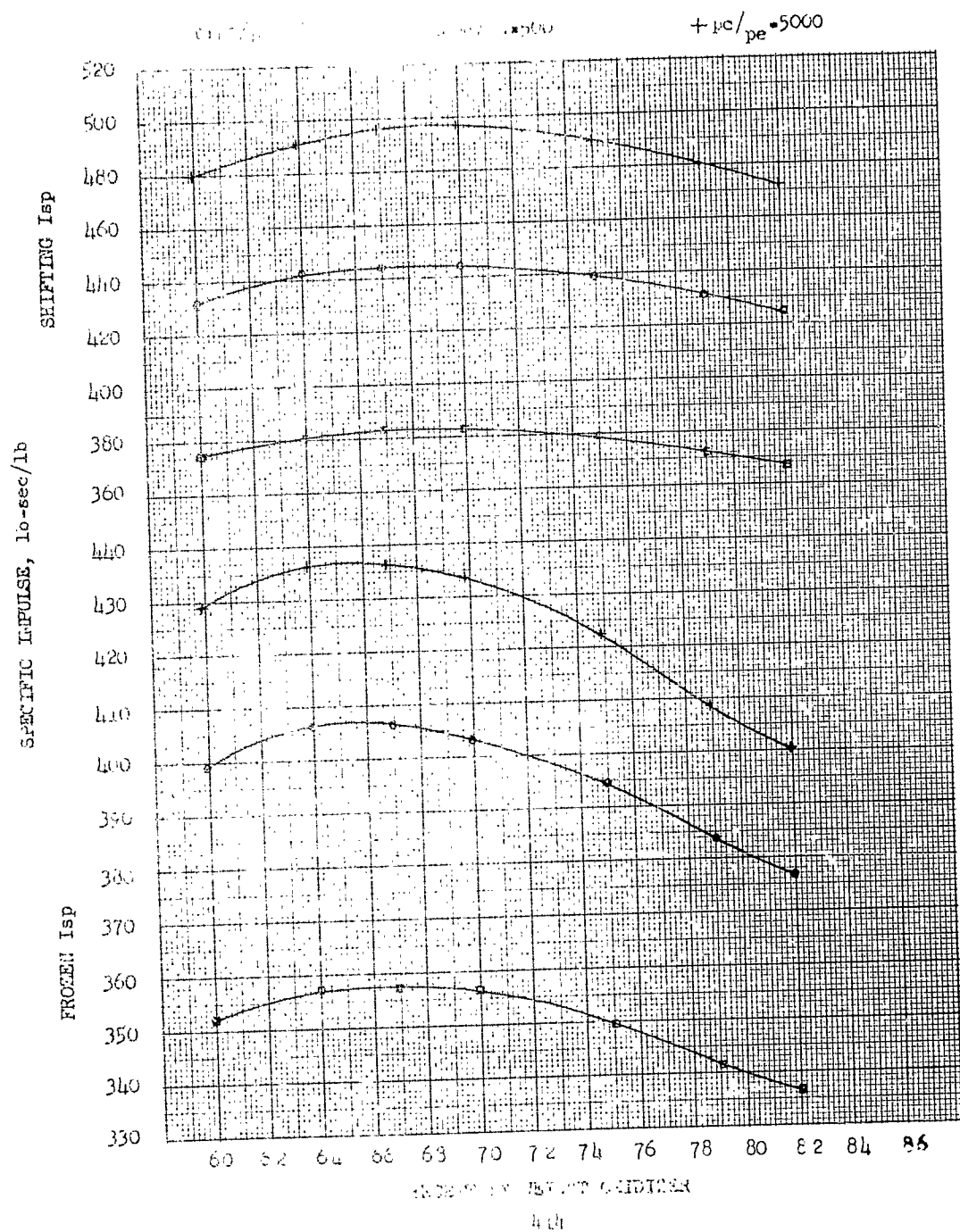
BERYLLIUM HYDRIDE - CATALYST FORMATION CURVE FIGURE 215

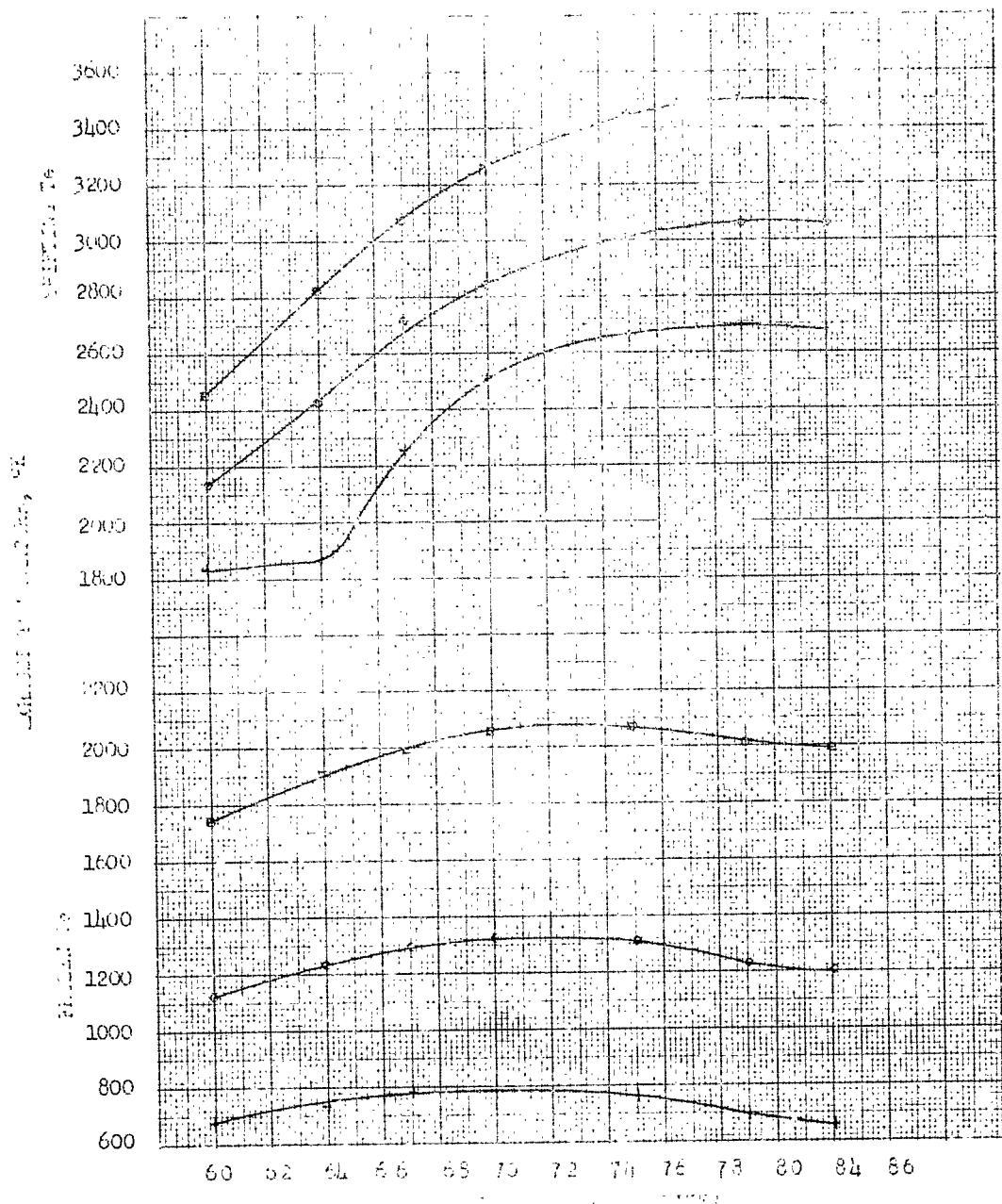


BERYLLIUM HYDRIDE - LIQUID PROPELLANT PERFORMANCE CURVES FIGURE 216

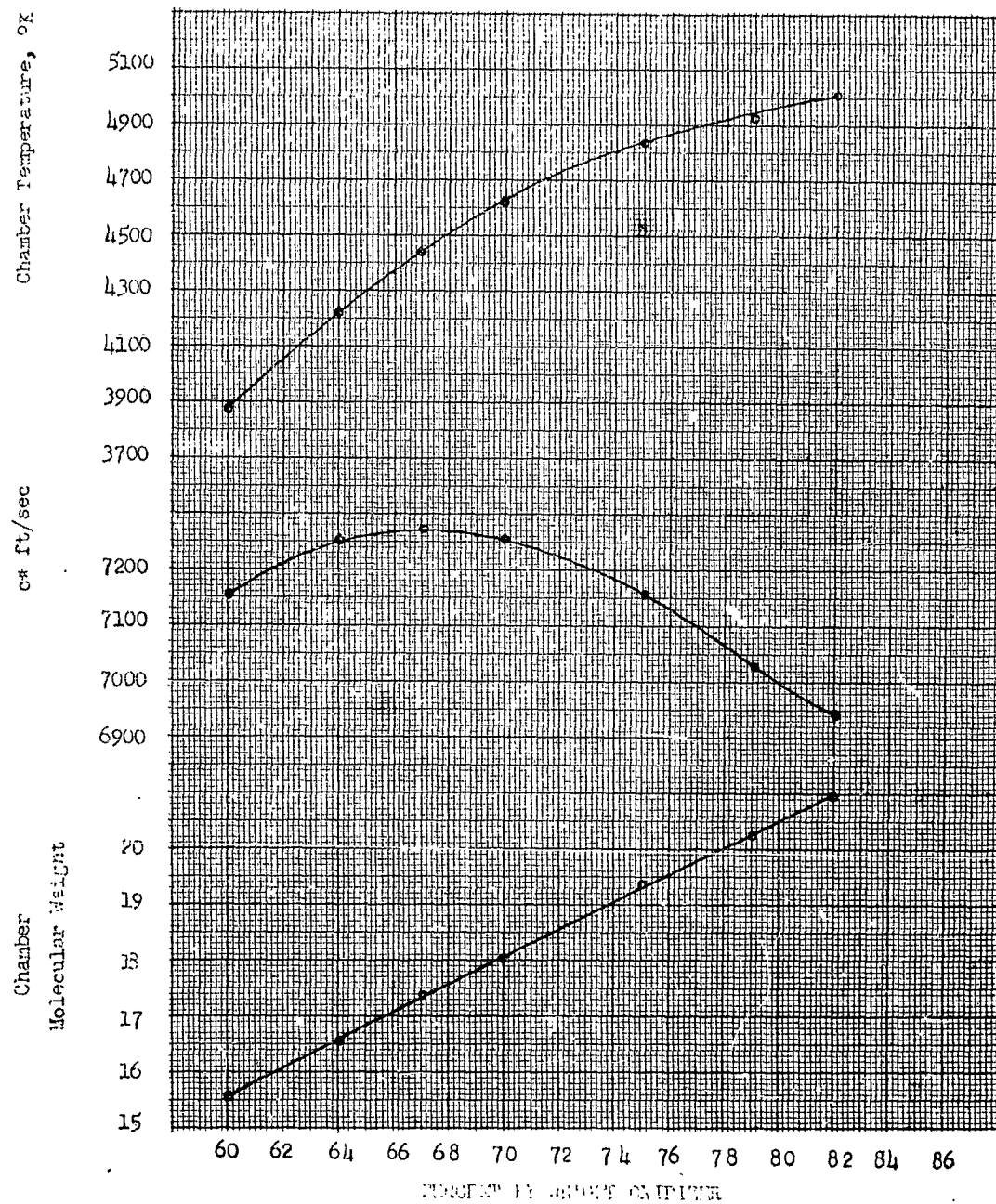


PERFORMANCE CURVES FIGURE 217





BERYLLIUM HYDRIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 219



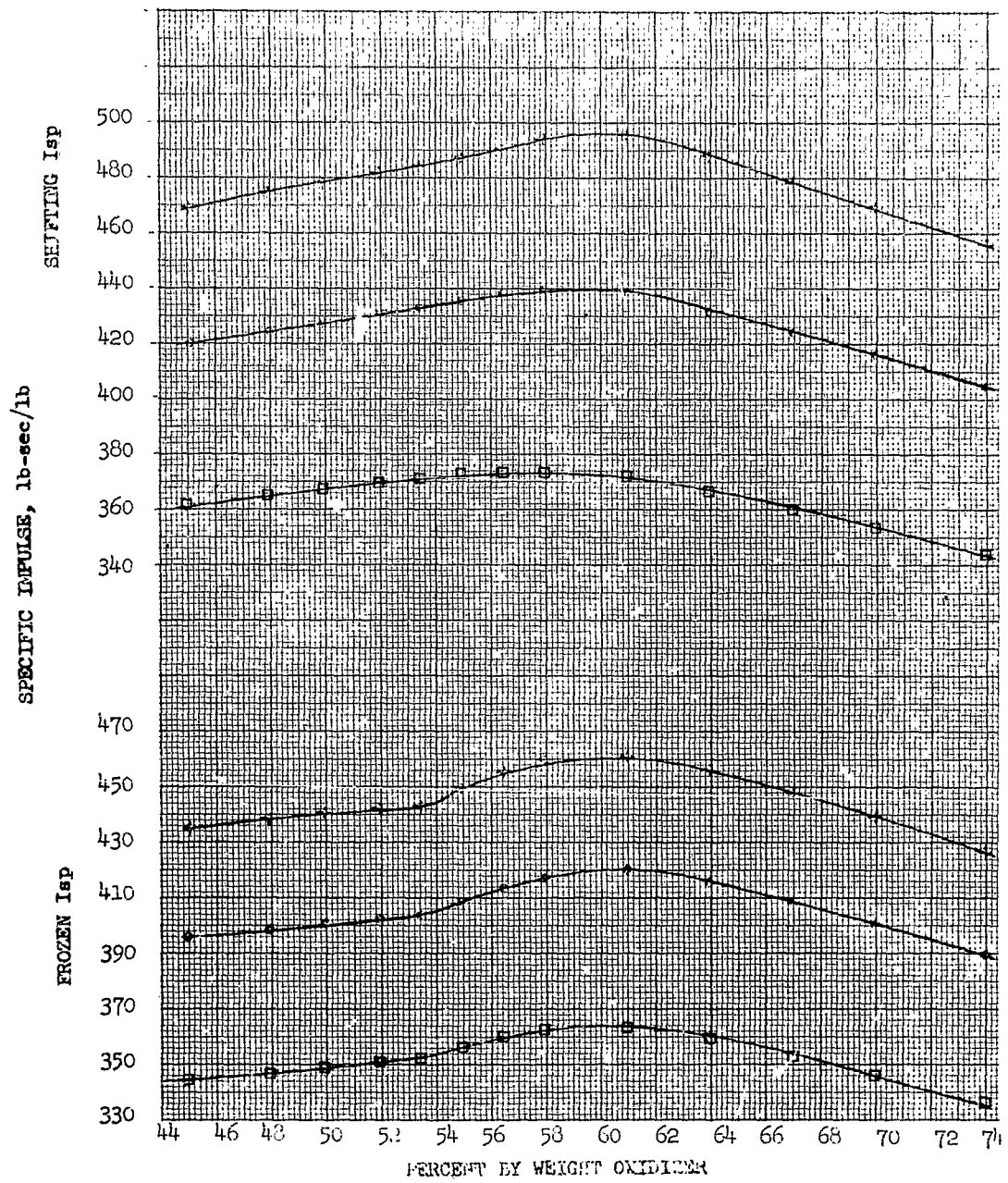
BERYLLIUM HYDRIDE - HYMOGEN BEROXIDE PERFORMANCE CURVES FIGURE 29

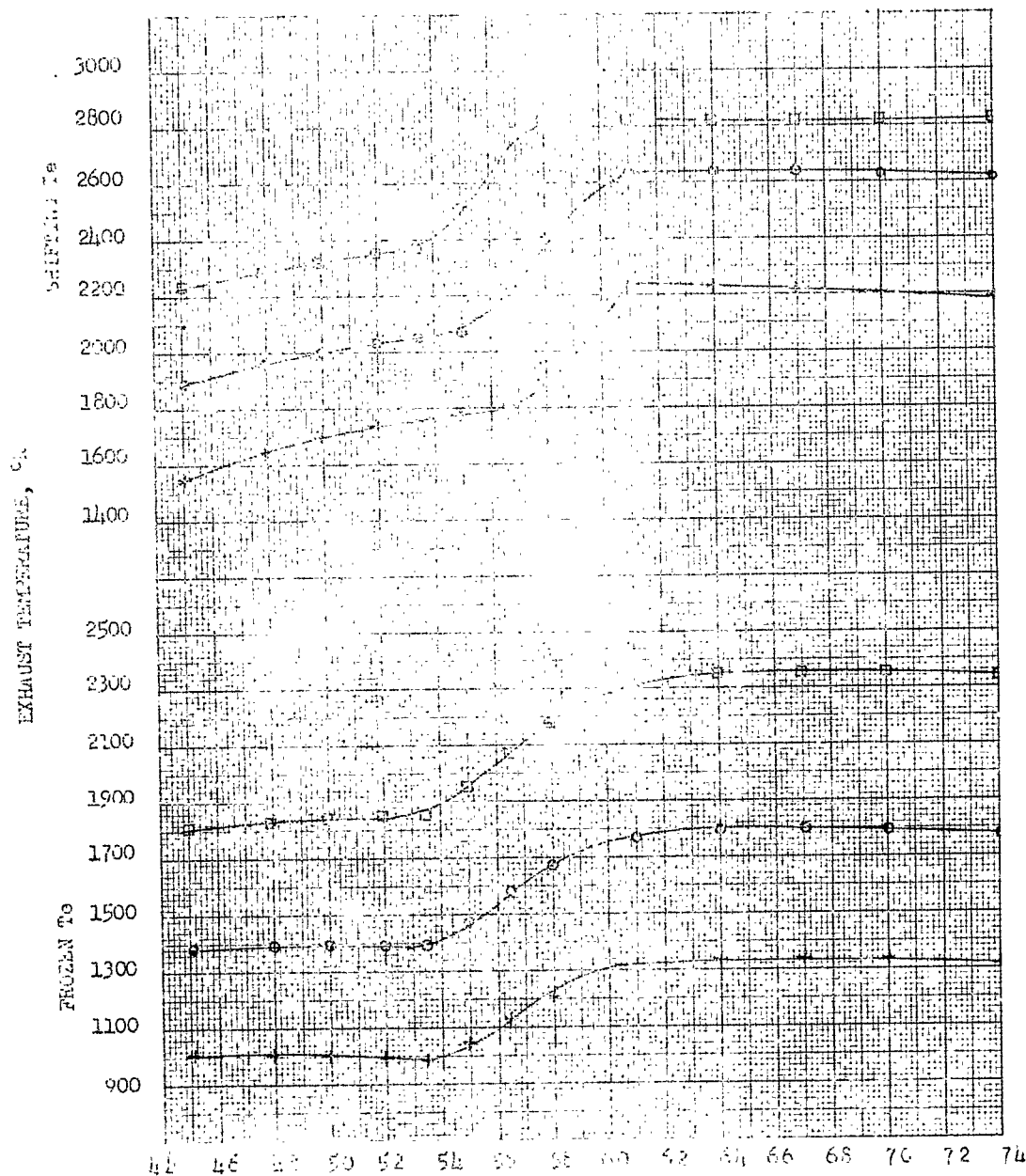
1000 psi

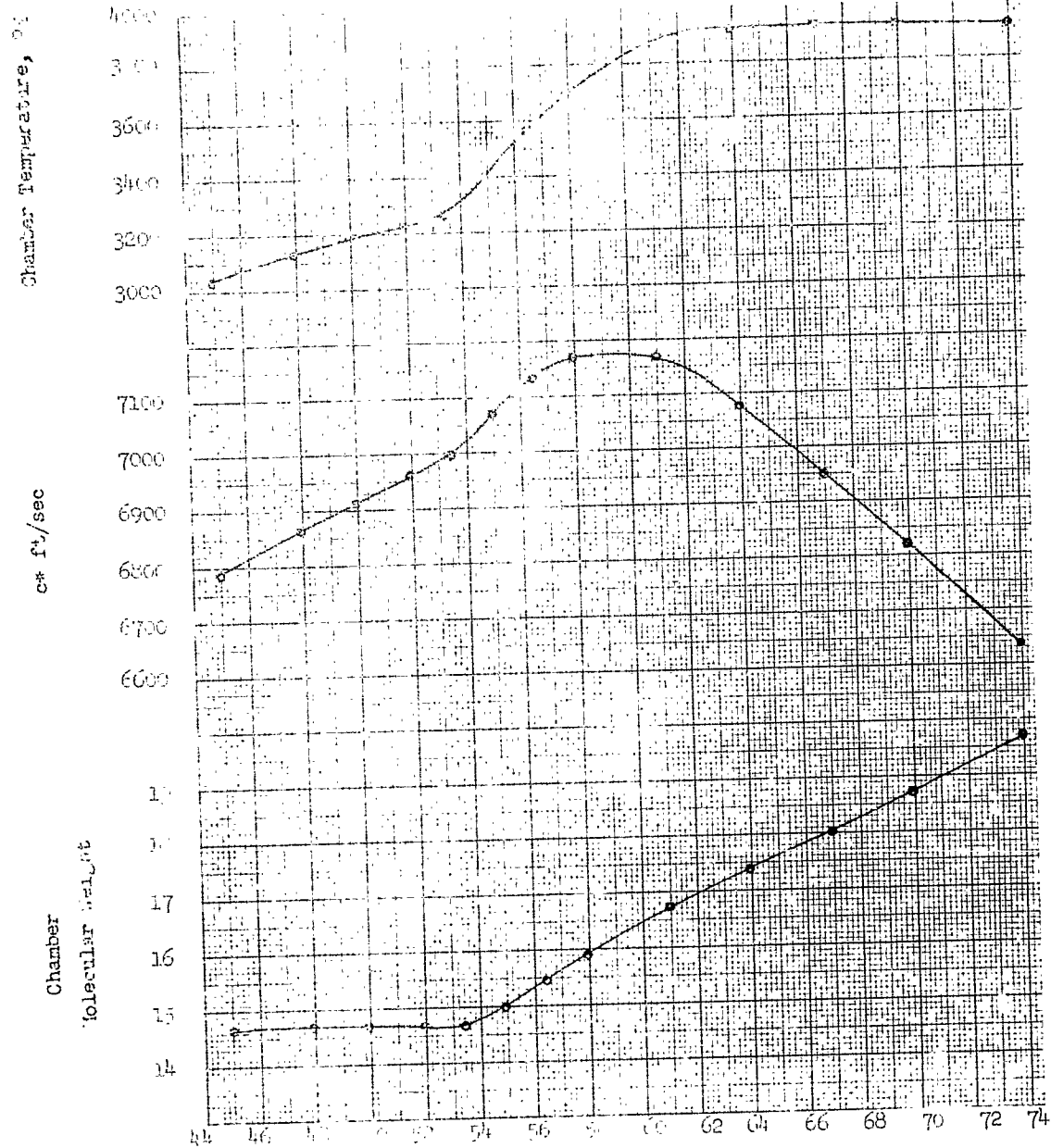
1000 psi

1000 psi

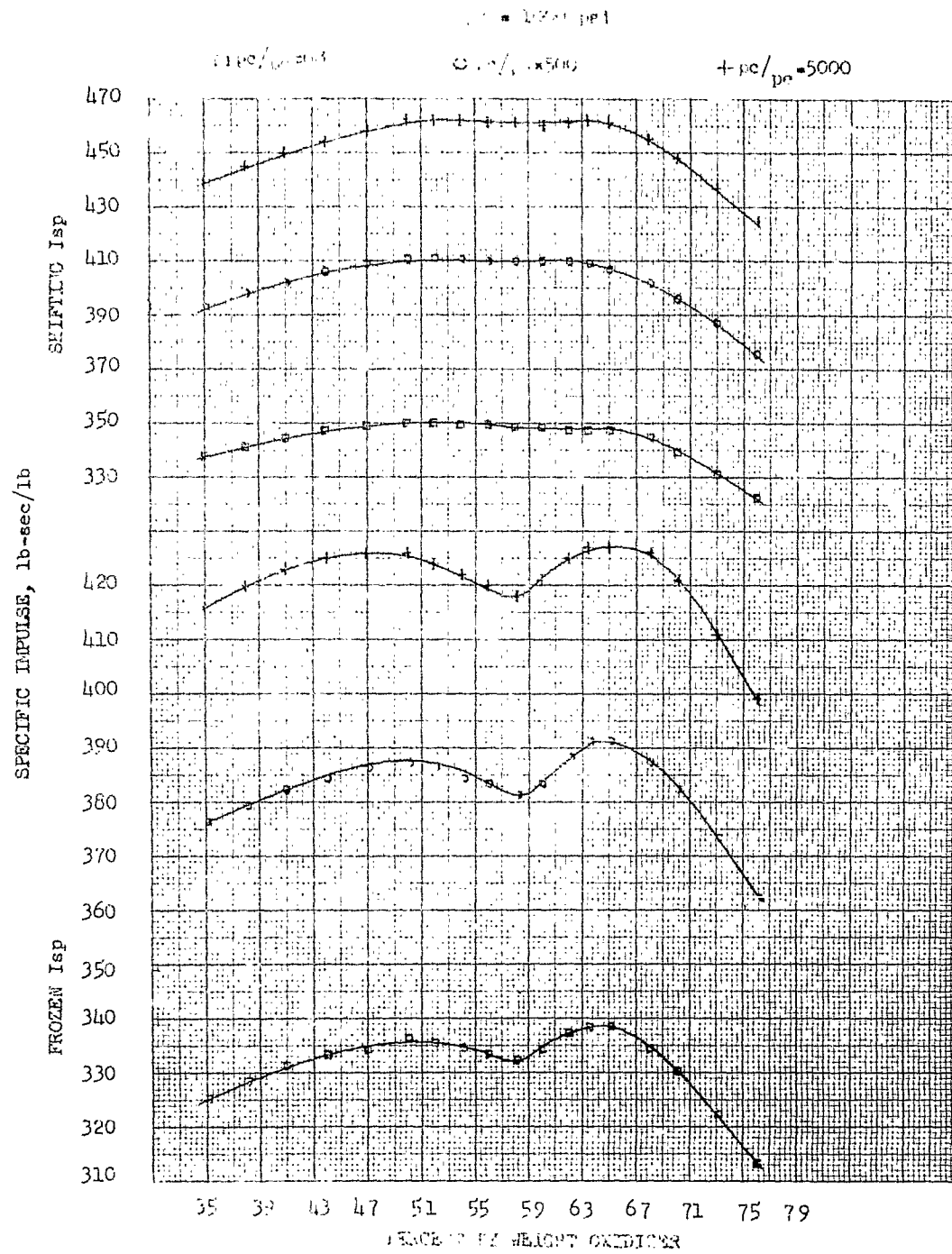
1000 psi



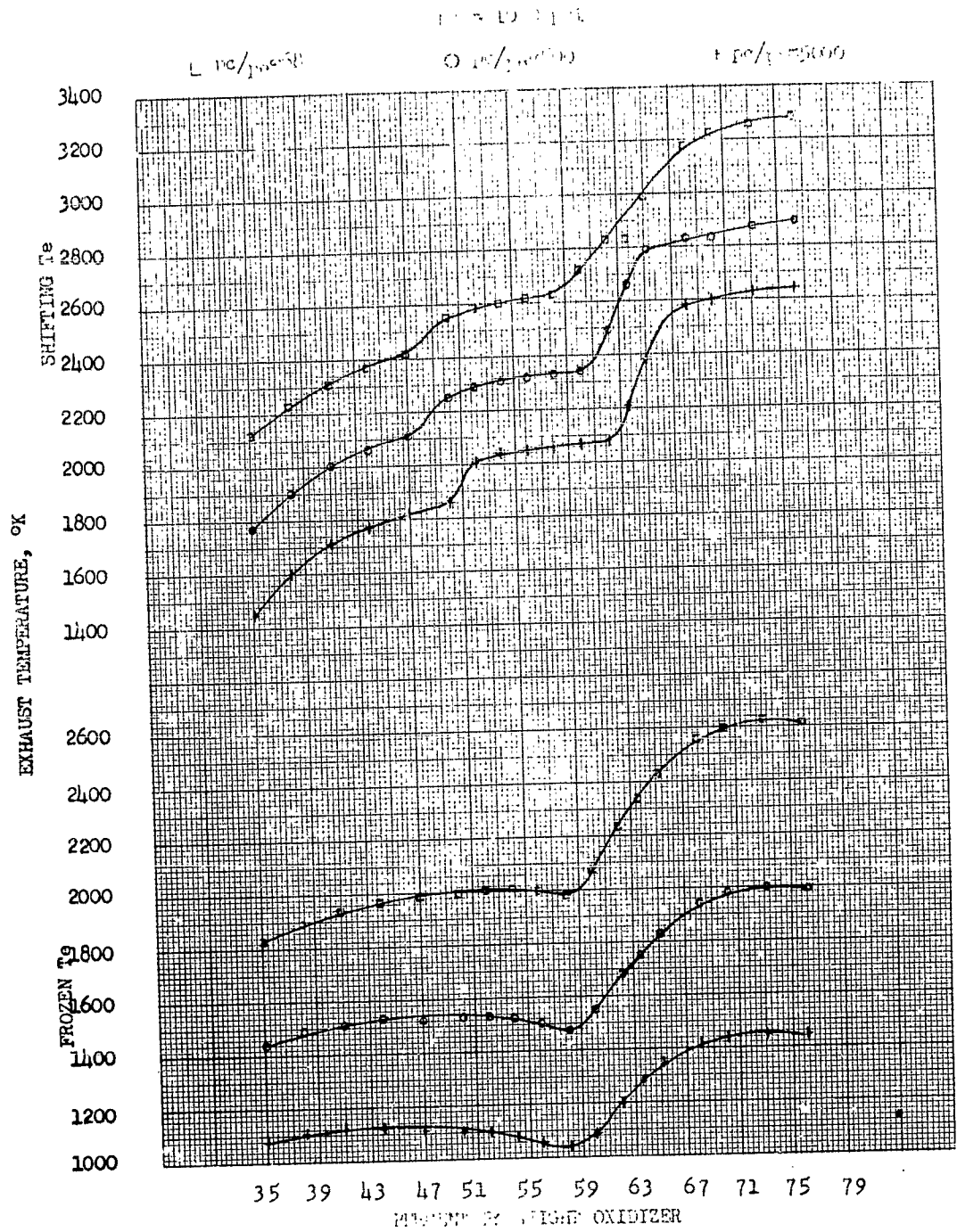




BERYLLIUM HYDROGEN FLUORIDE PERFORMANCE CURVES FIGURE 223



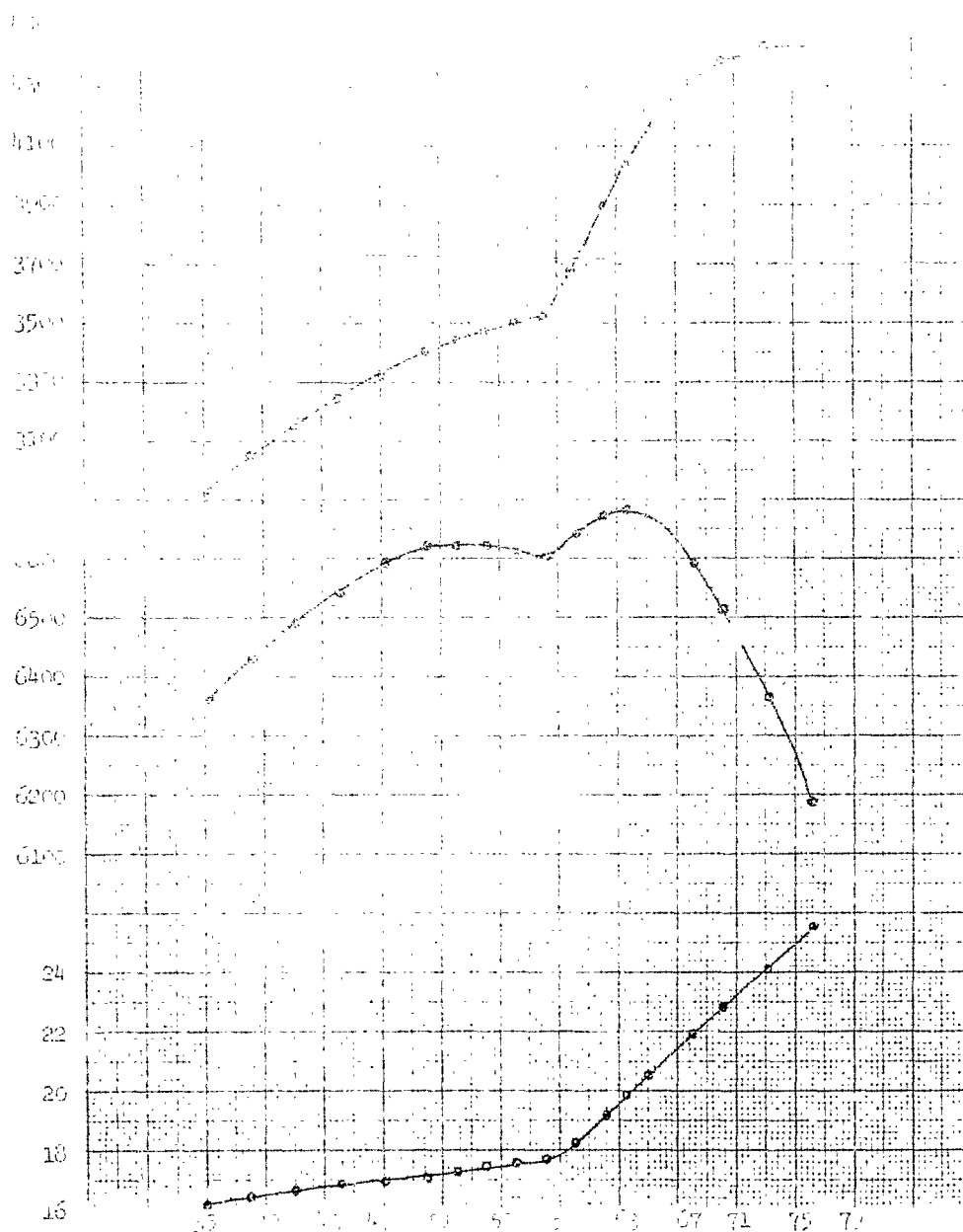
BERYLLIUM HYDRIDE - 11 TROGEN TETROXIDE PERFORMANCE CURVES FIGURE 224

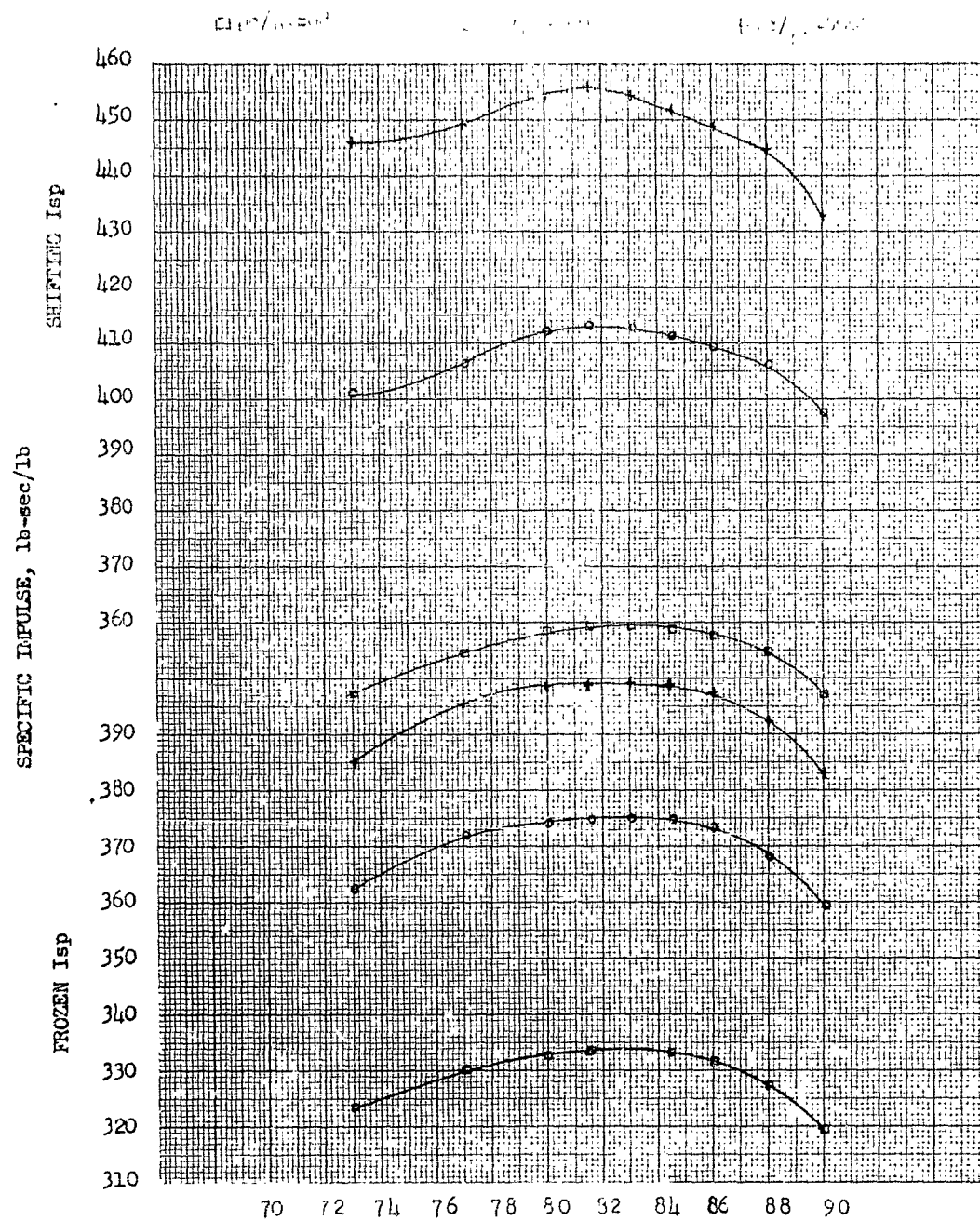


Chamber Temperature

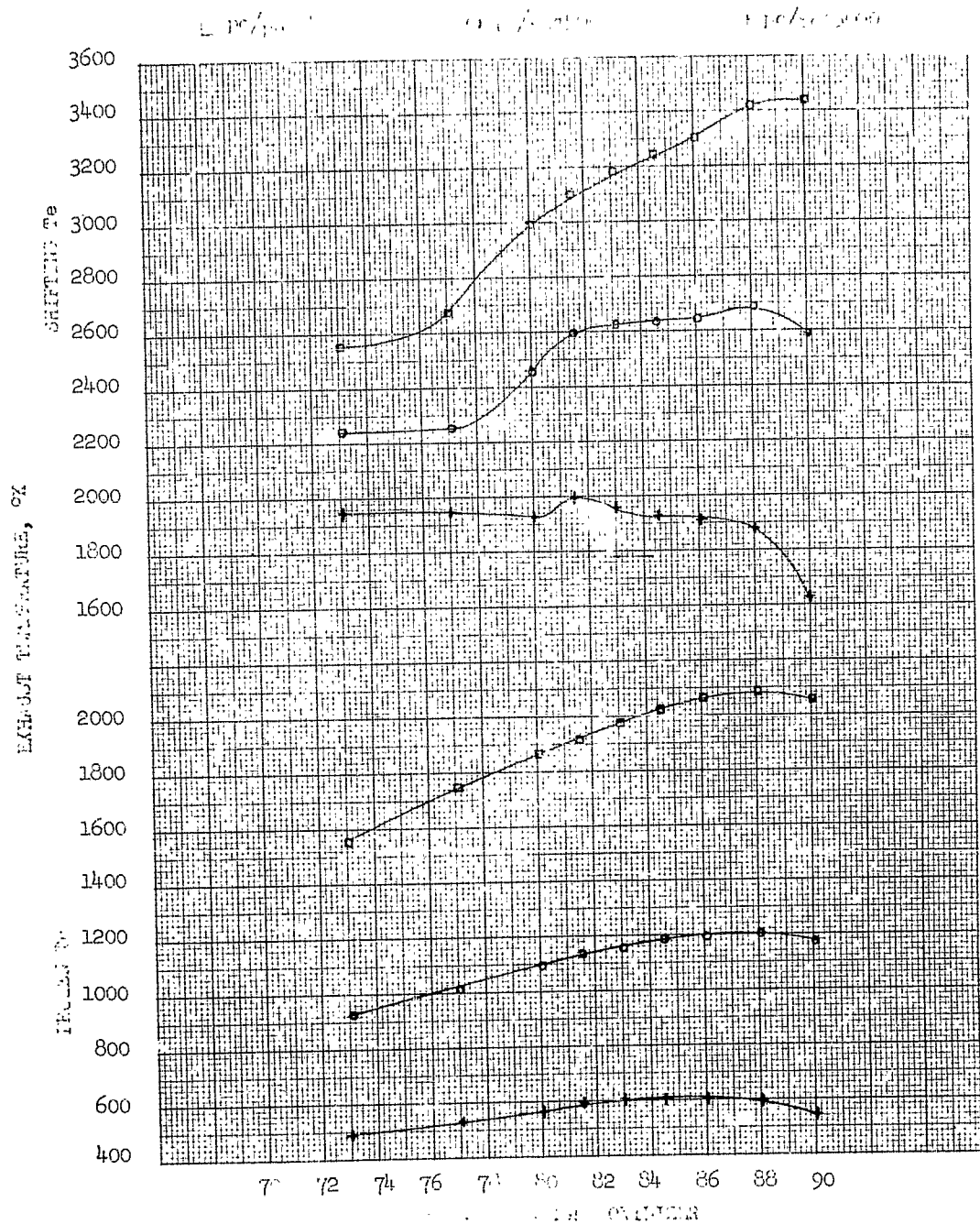
cm ft/sec

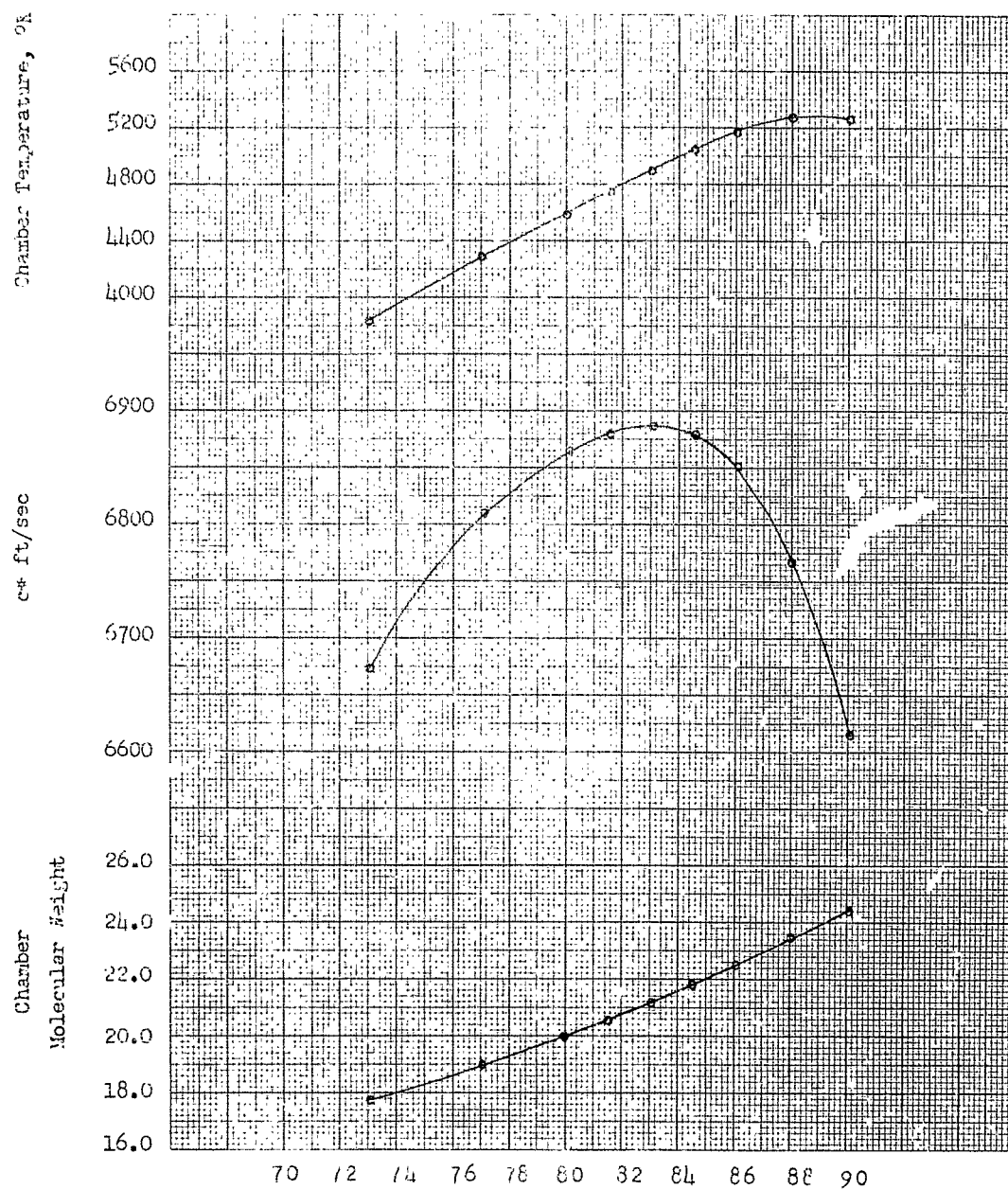
Chamber
Molecular Weight



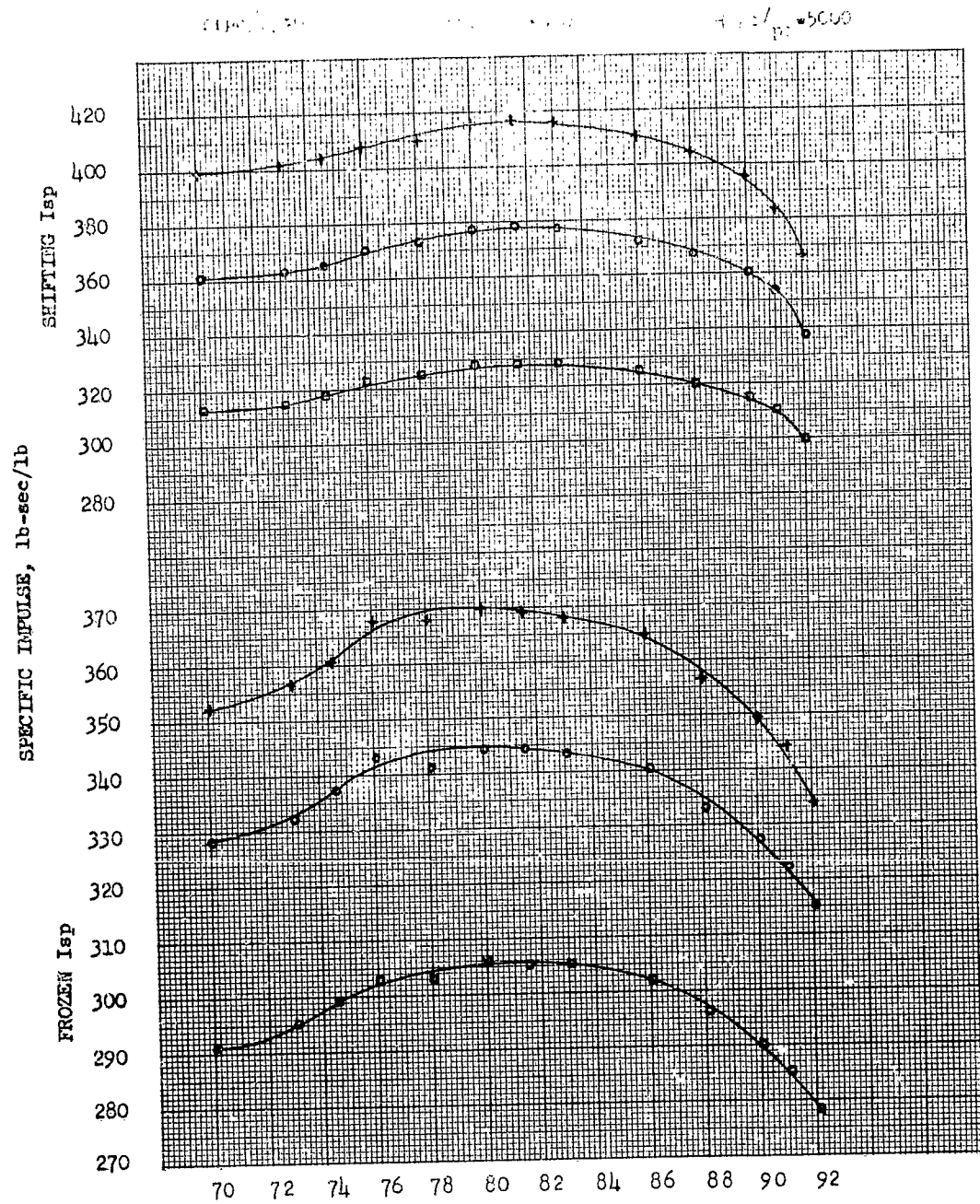


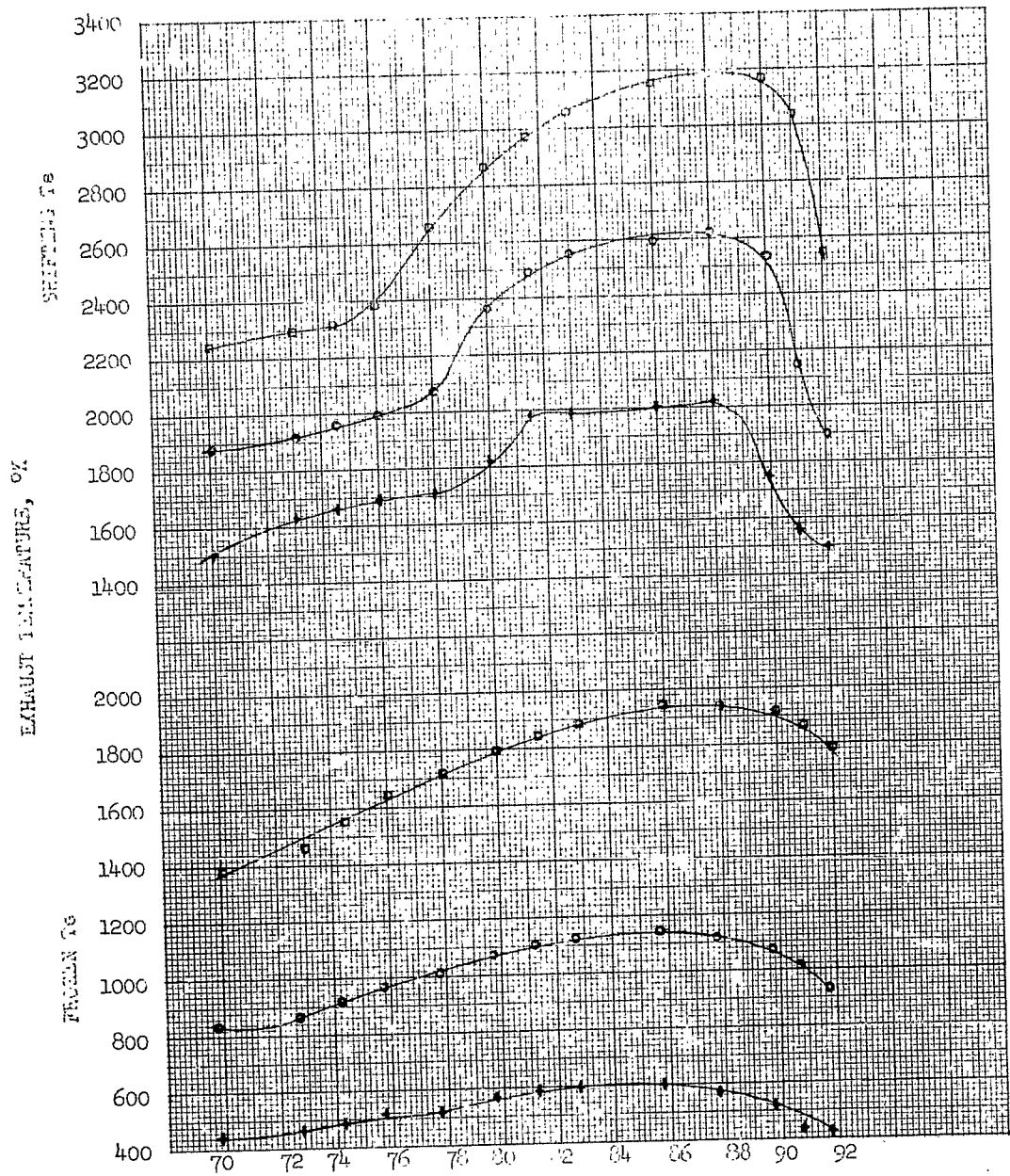
BERYLLIUM FLUORIDE - HYDROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 1-27

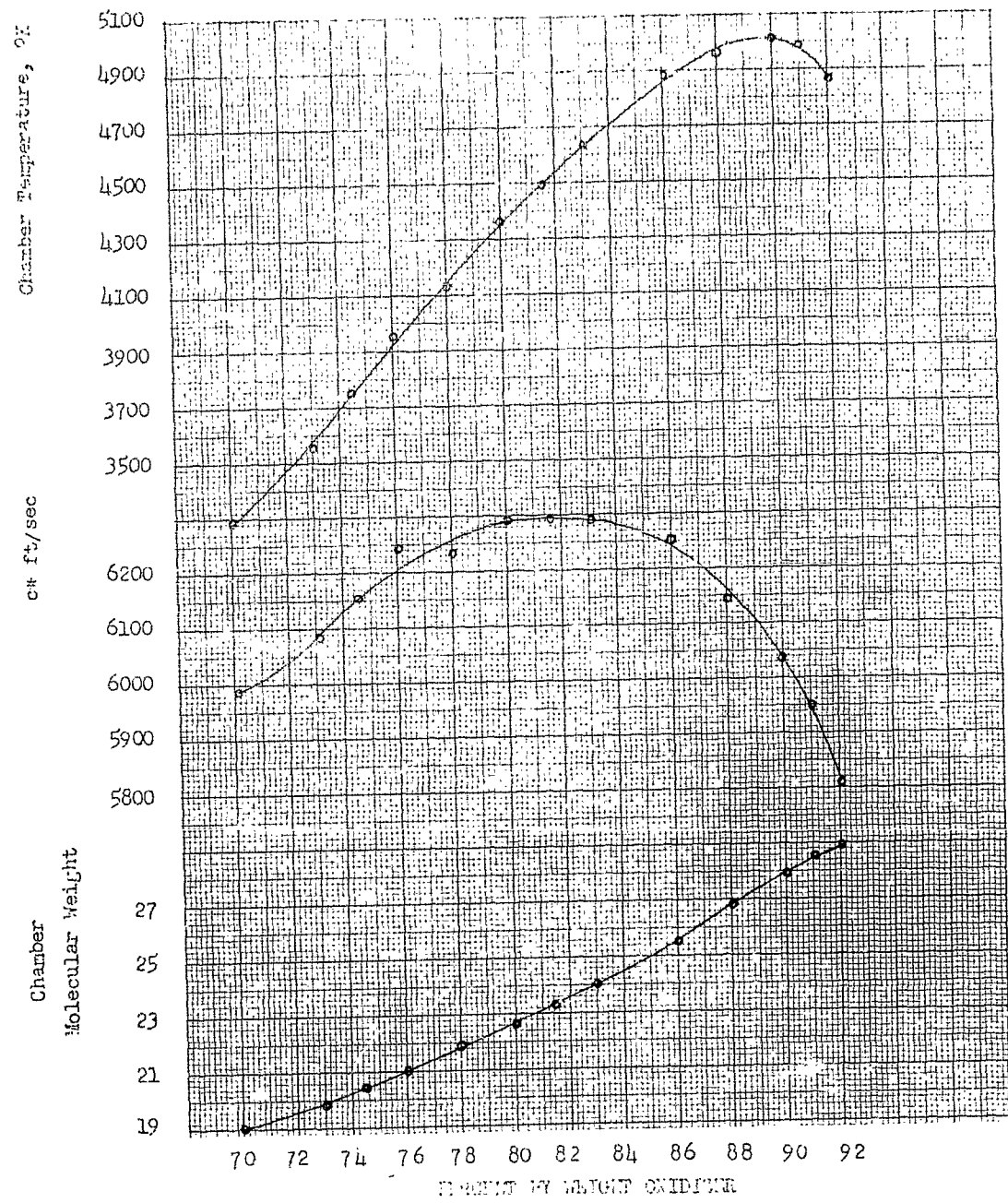




BERYLLIUM HYDROXIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 229







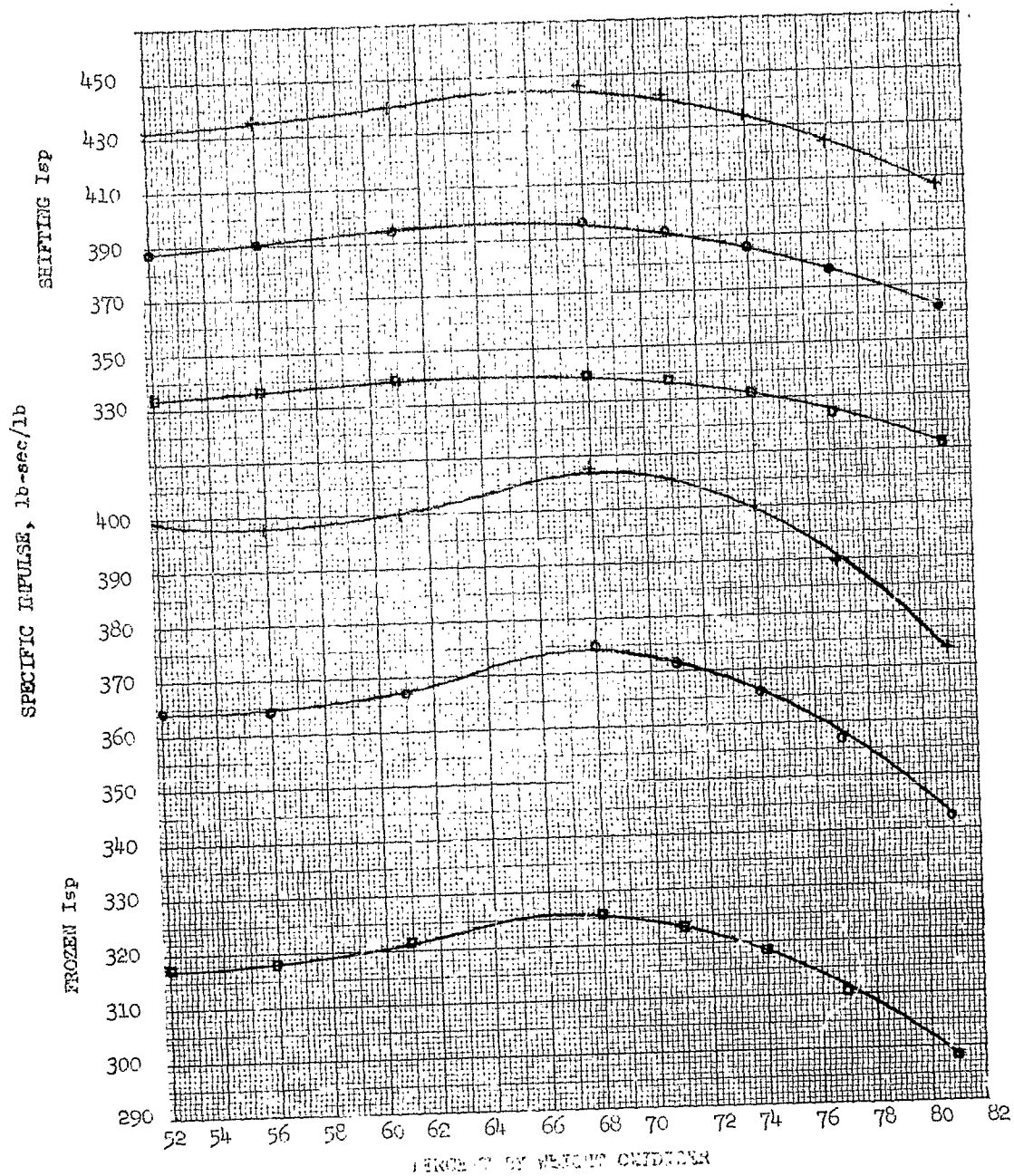
BERYLLIUM FLUORIDE - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 232

100 psi

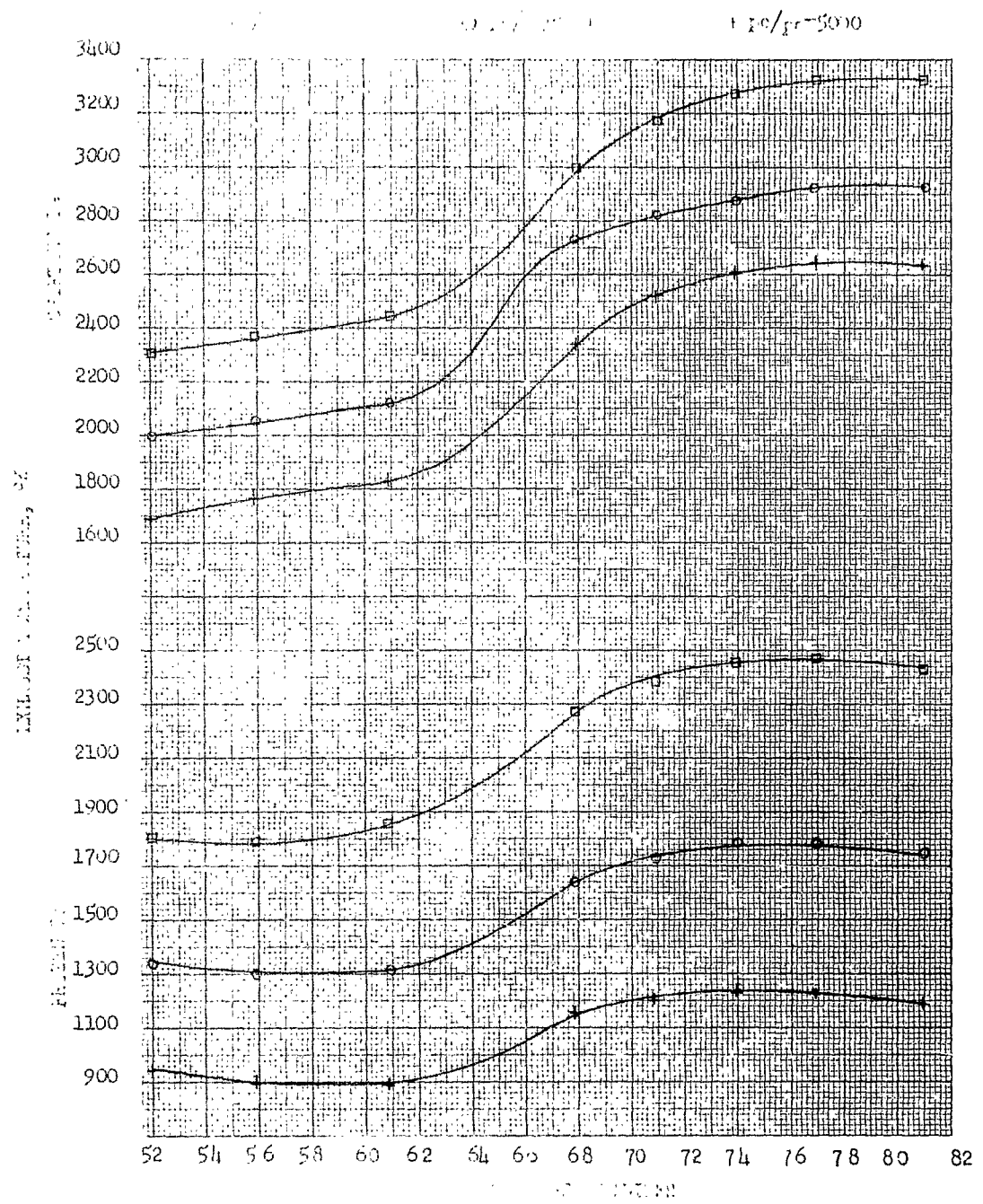
100 pc/gm. sub

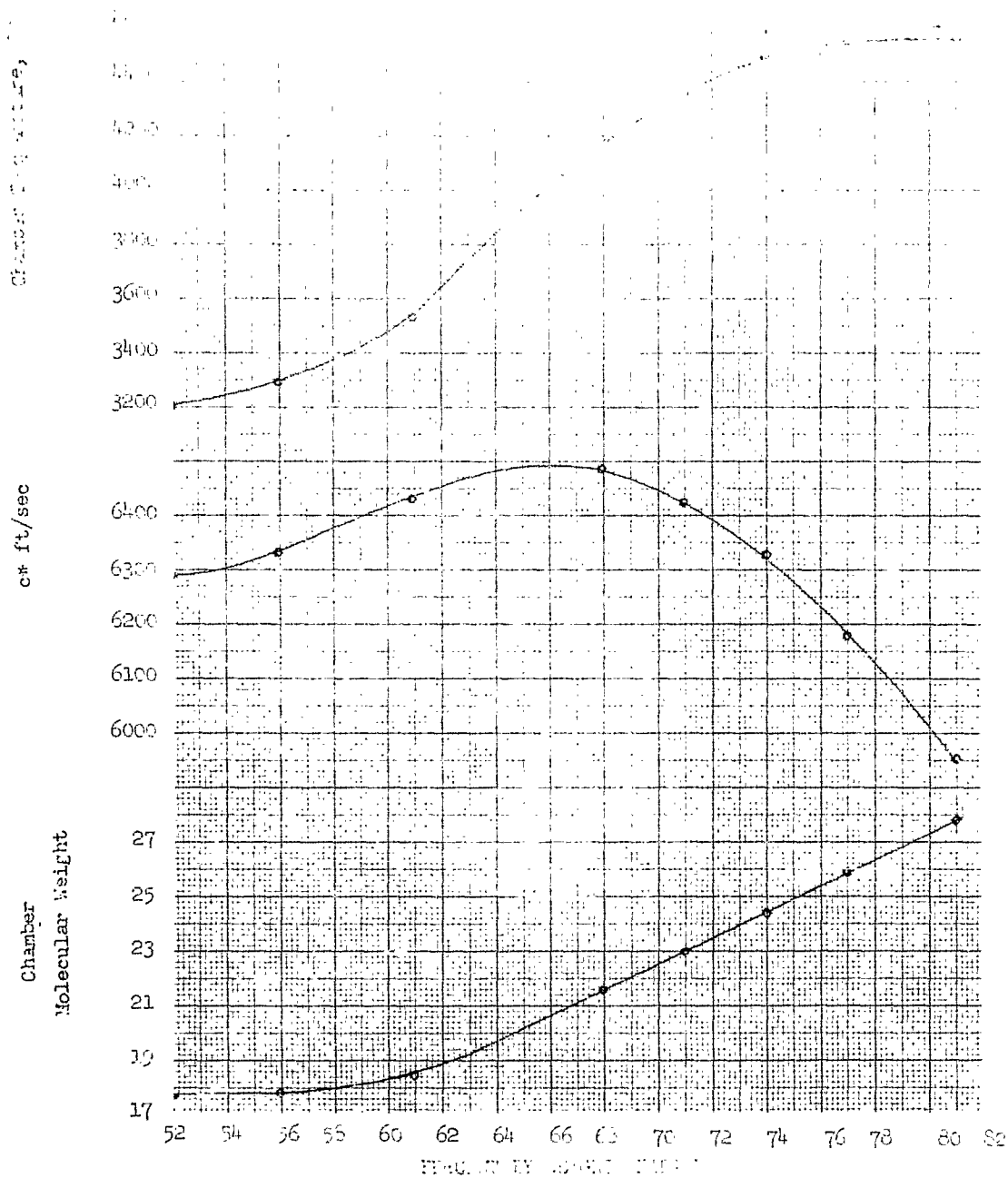
100 pc/gm. sub

100 pc/gm. sub

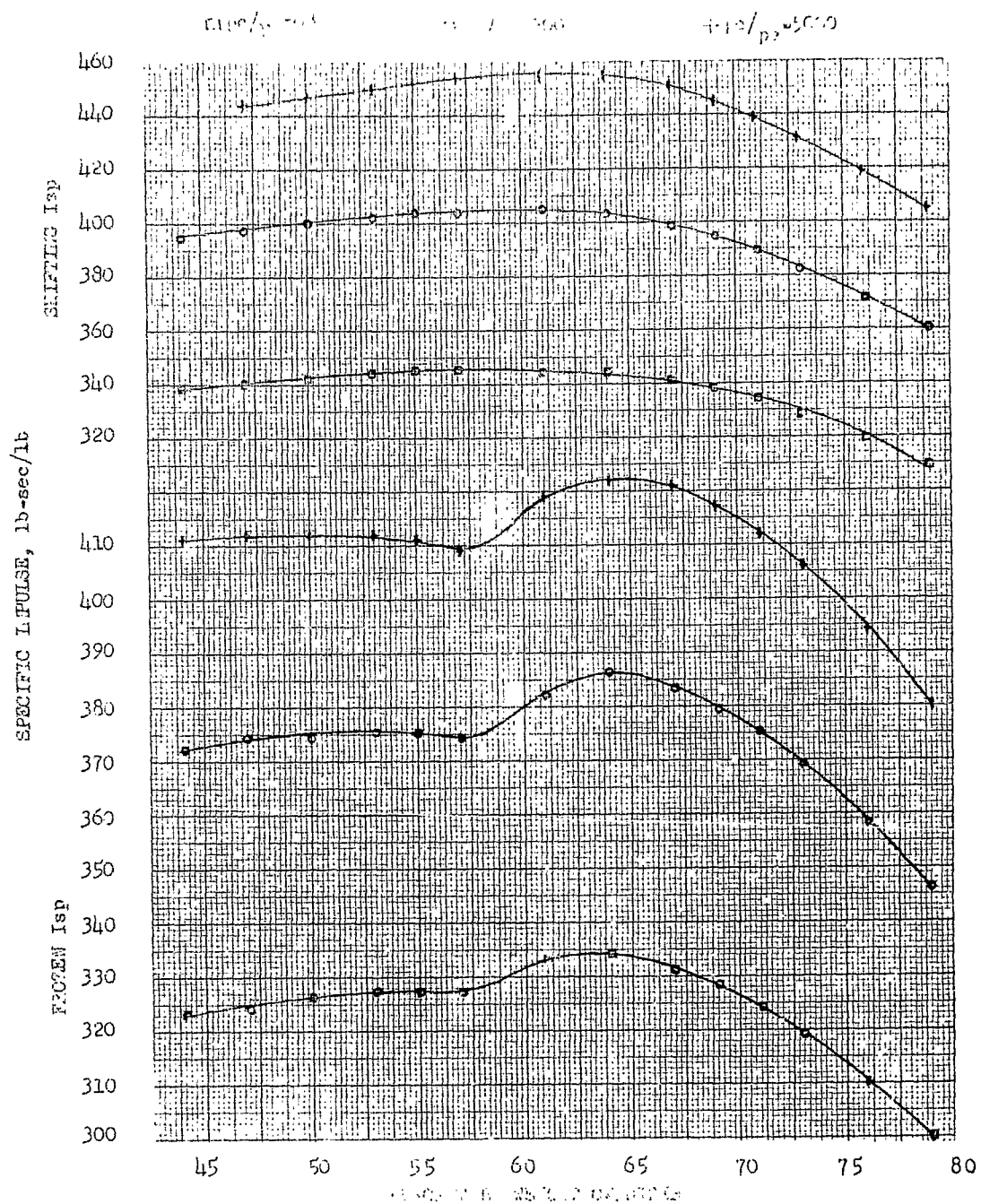


PERFORMANCE OF 1000-5000 FLOORING PERFORMANCE CURVES FIGURE 233

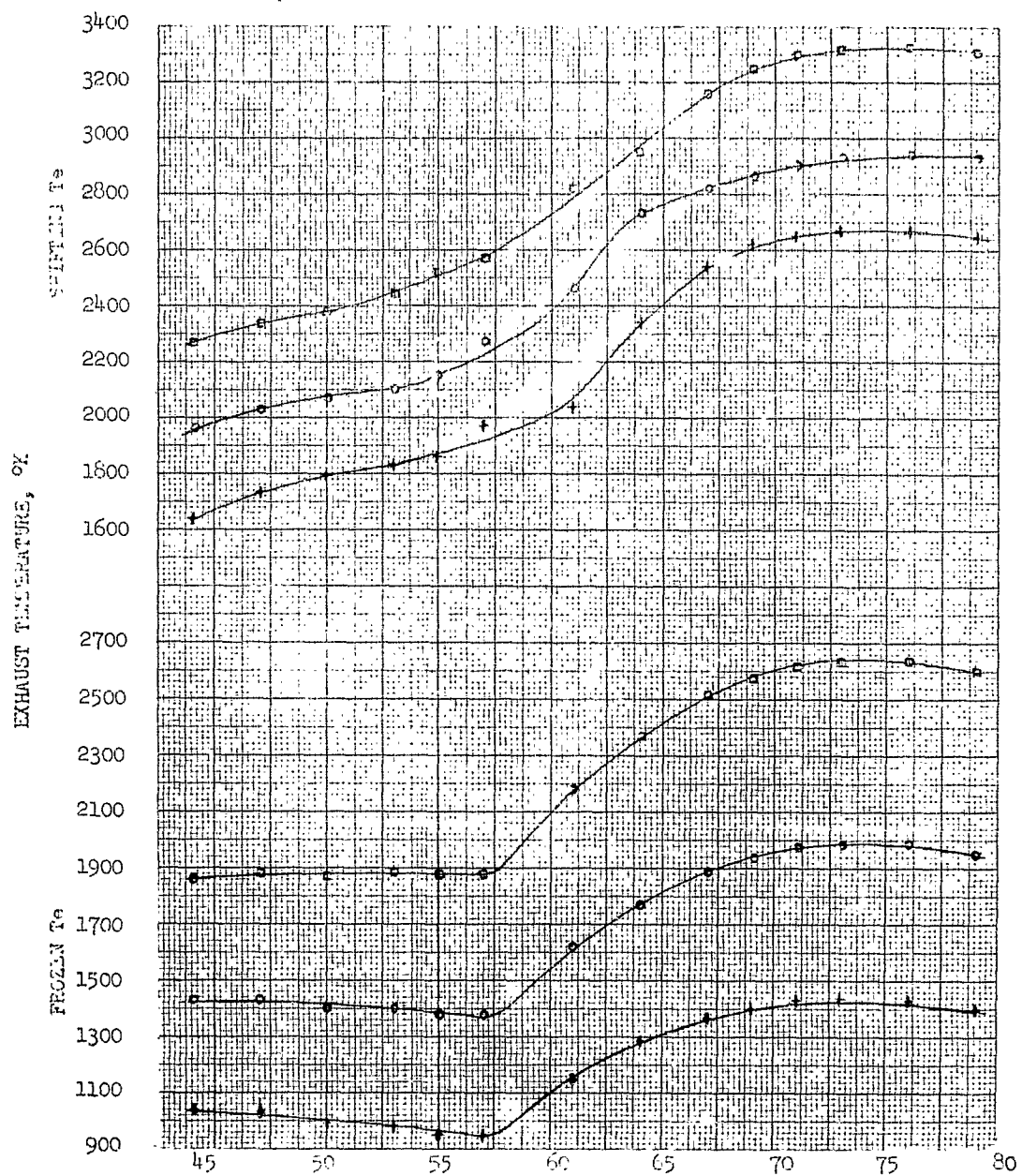




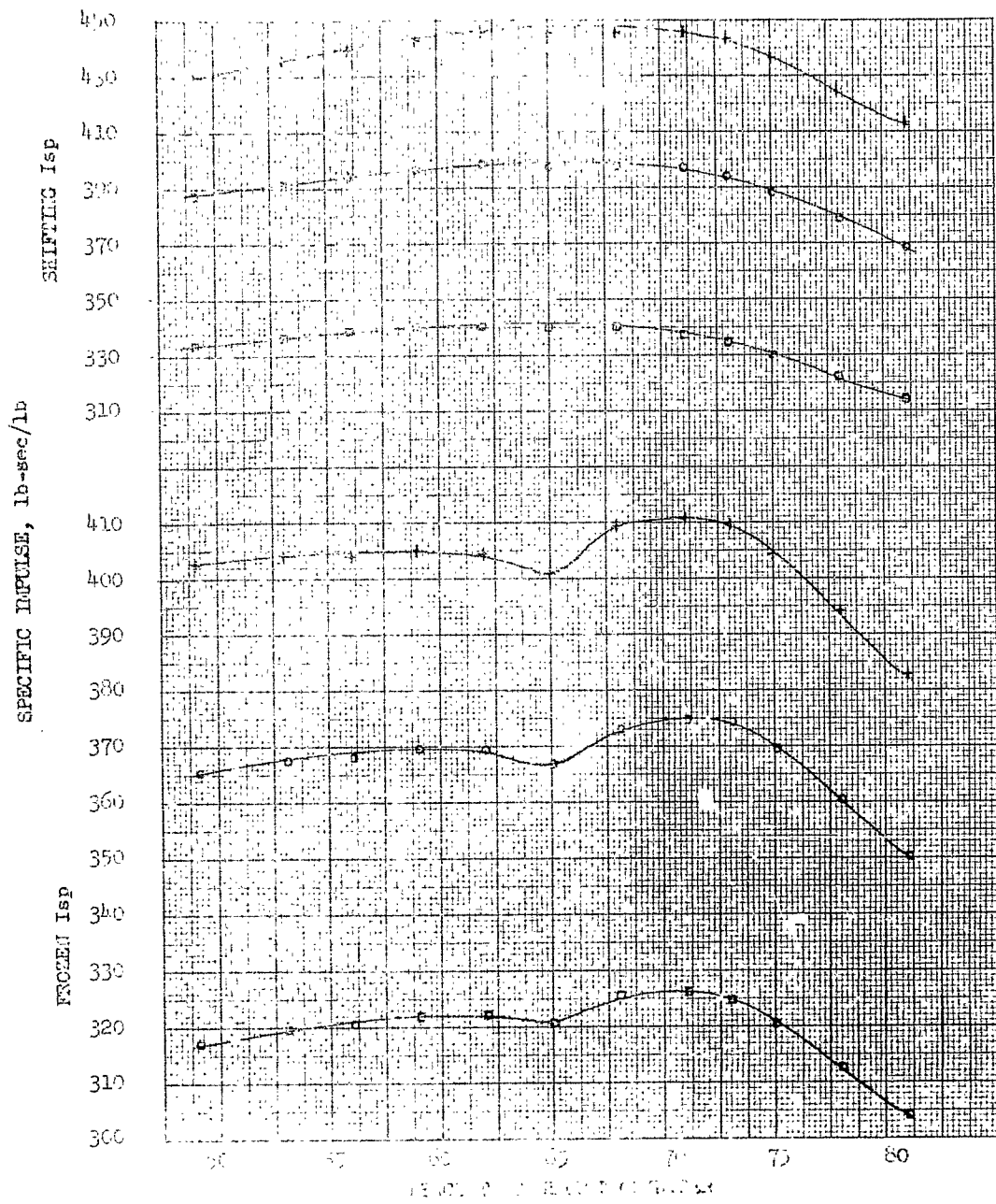
AMMONIUM HYDROXIDE - CONTROLLED FERTILIZER PERFORMANCE CURVES FIGURE 235

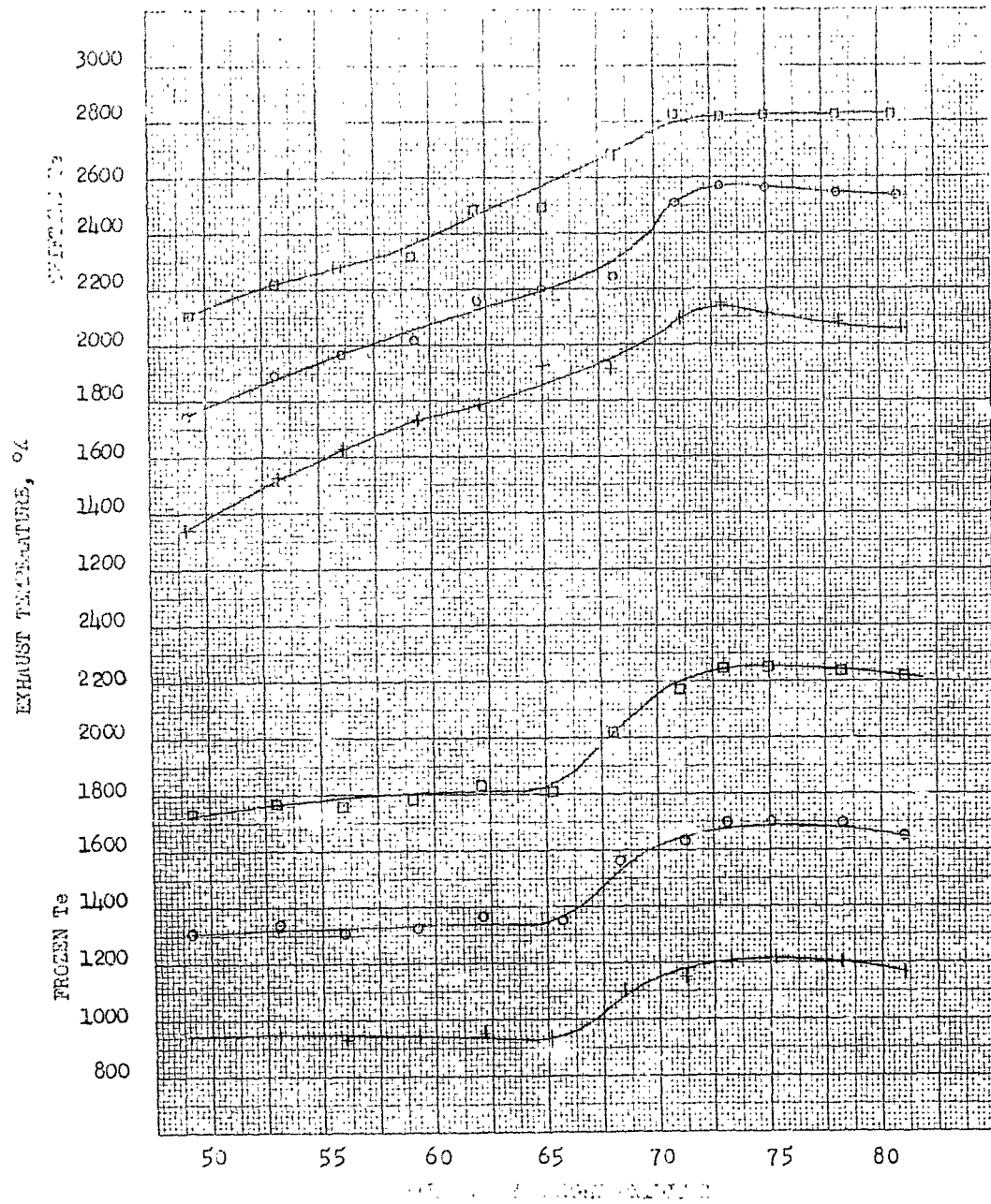


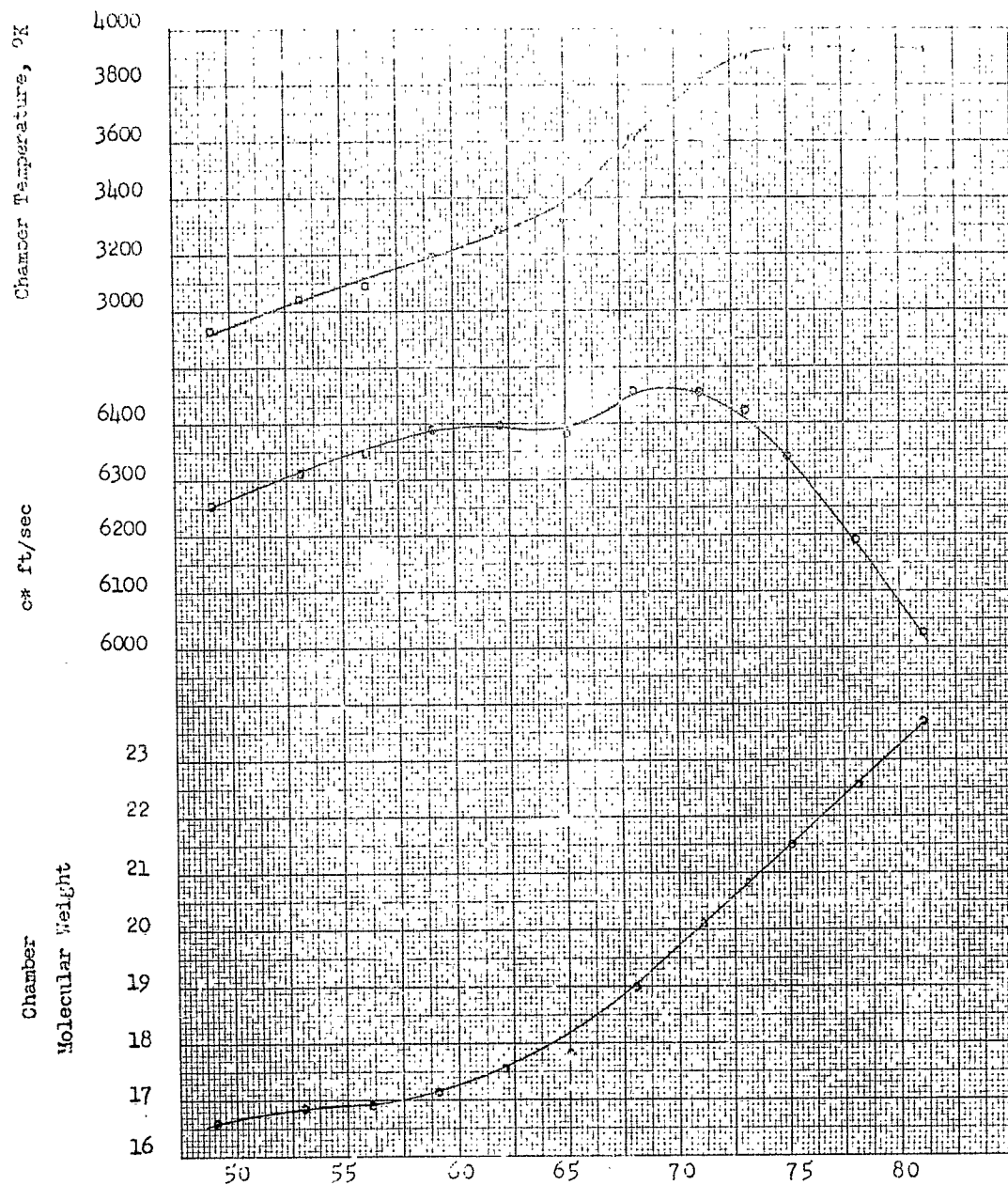
BERYLLIUM HYDRIDE - THERMAL DECOMPOSITION CURVES FIGURE 230

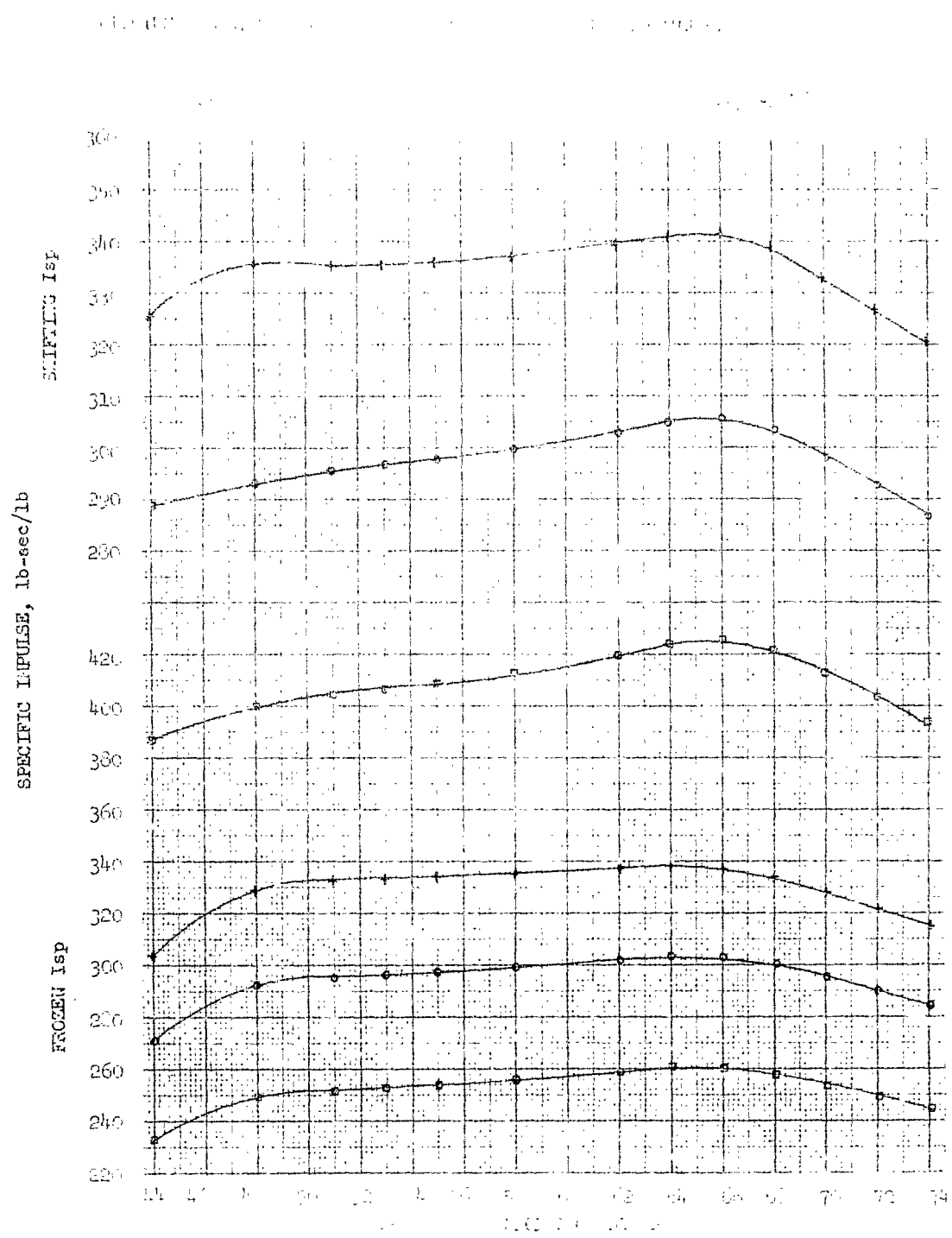


4-12-50

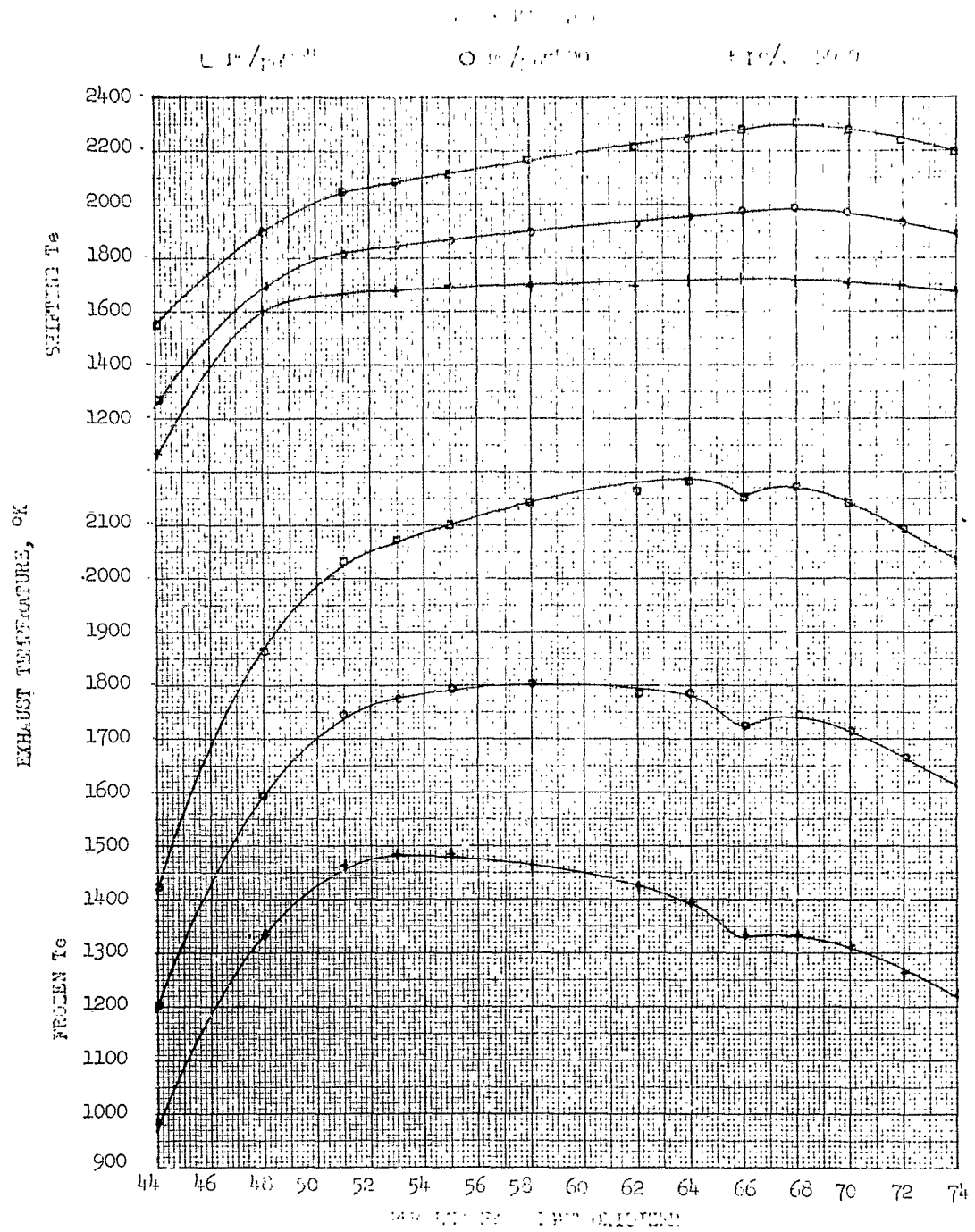


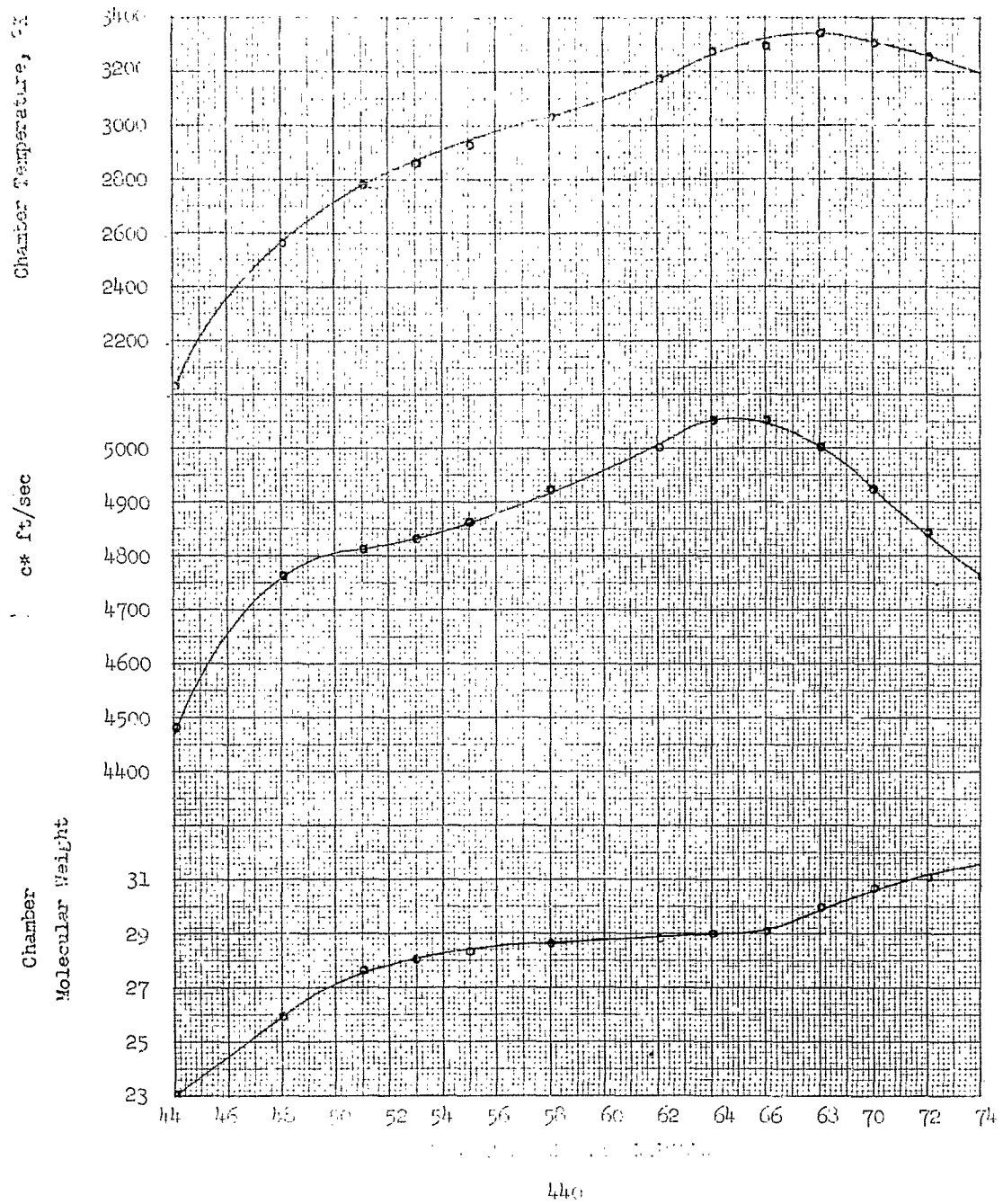




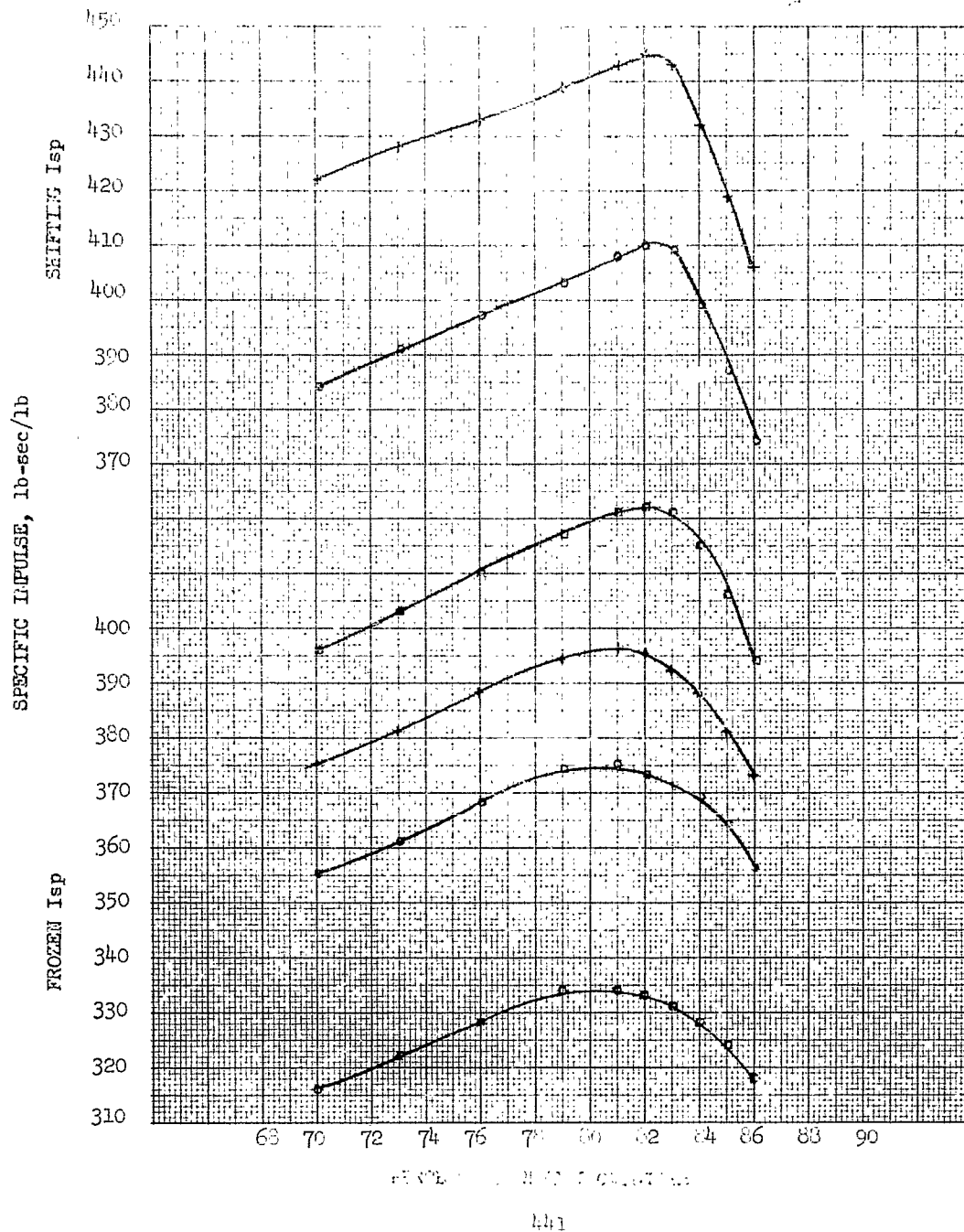


LITHIUM HYDRIDE - LIQUID CRYSTAL TEMPERATURE CURVES FIGURE 29a



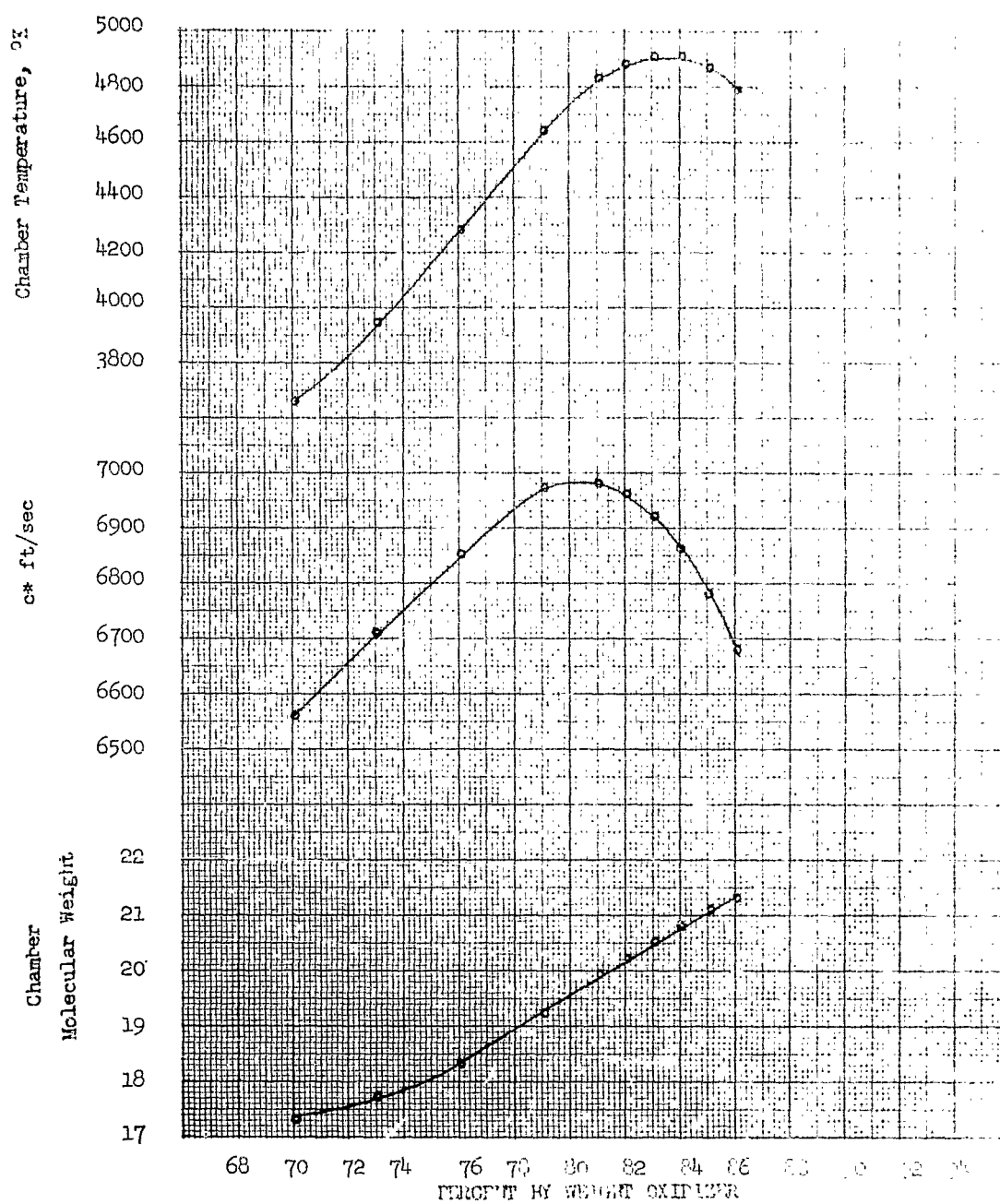


1000/1000000

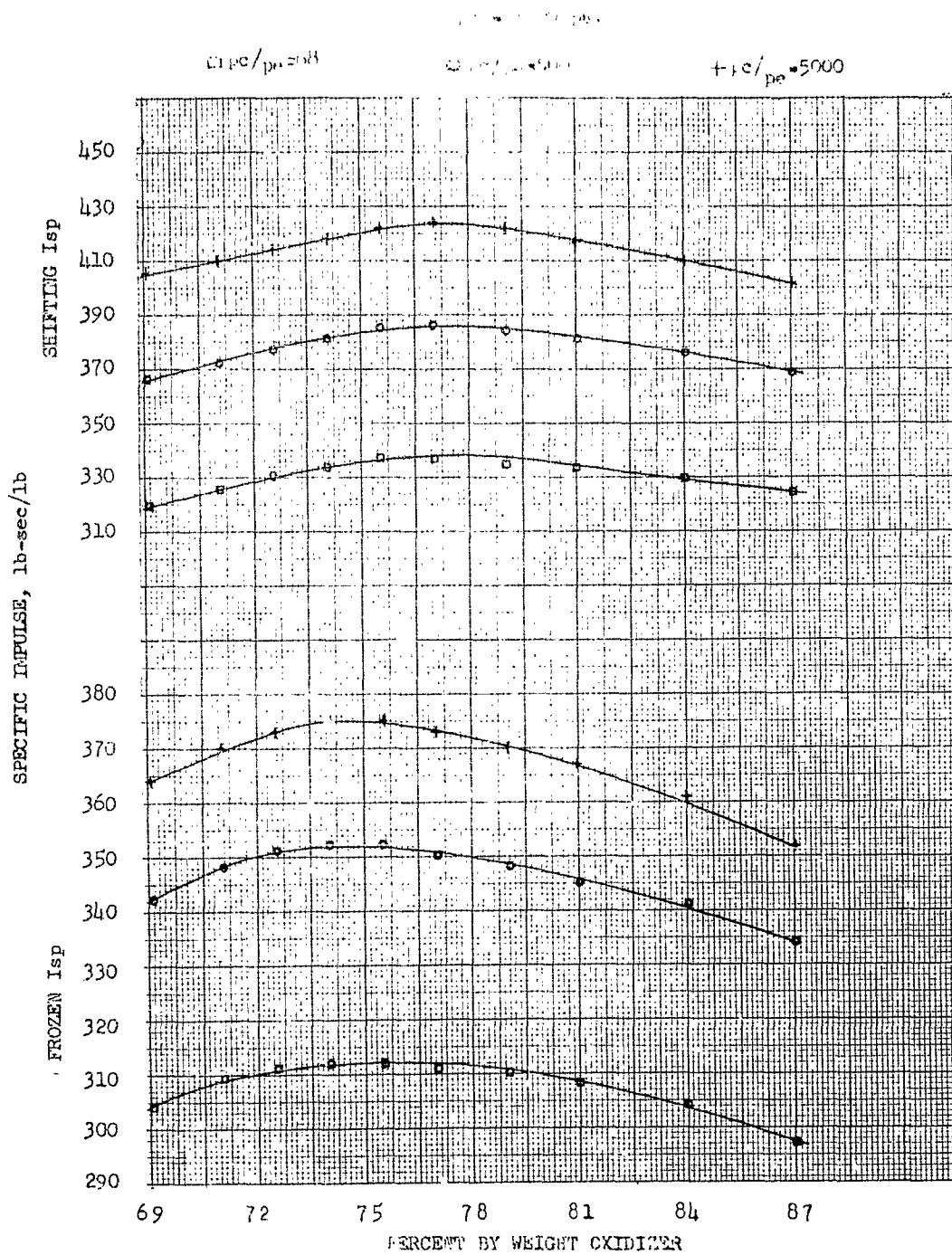




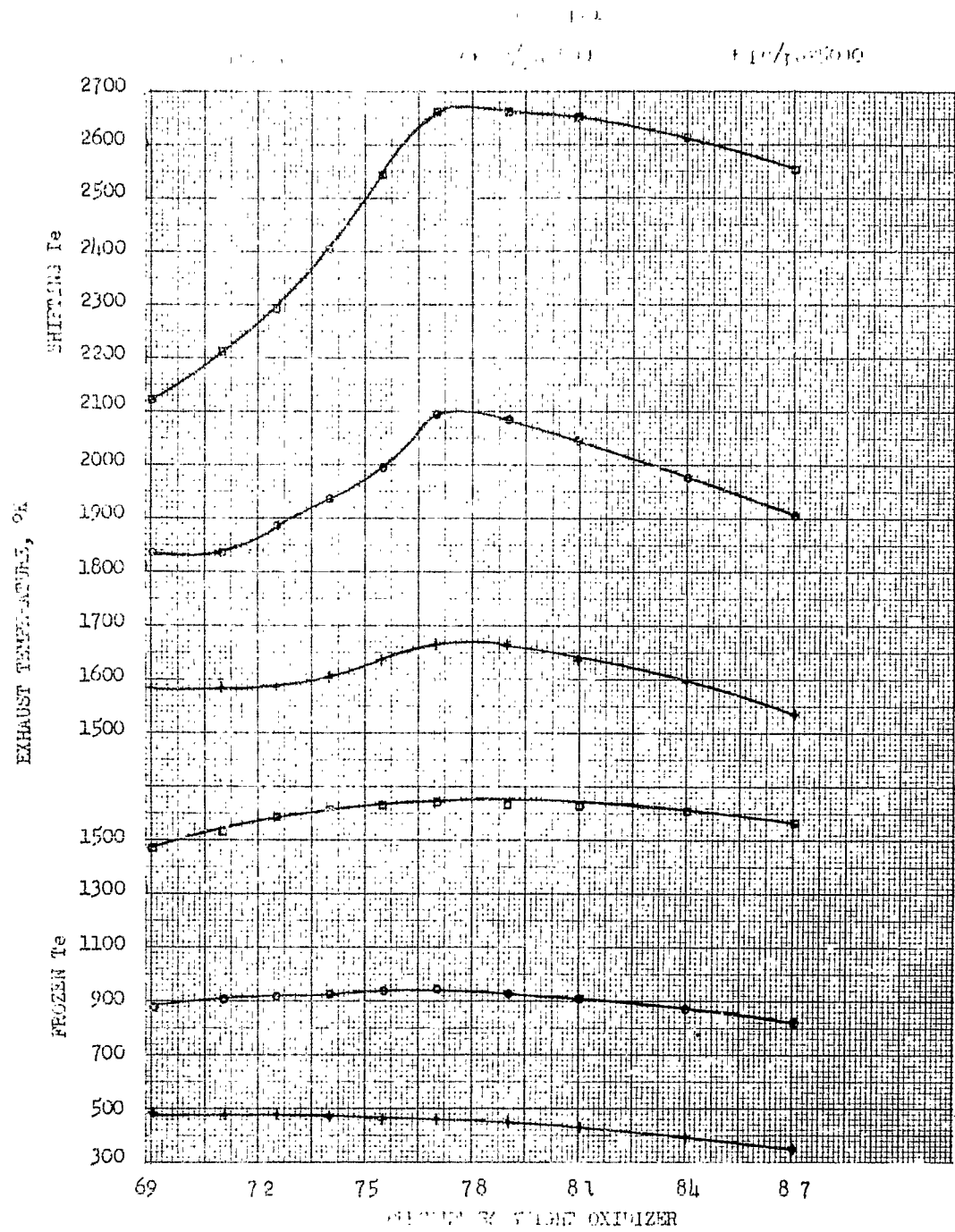
LITHIUM BORIDE - LIQUID FLUORIDE PERFORMANCE OF NO. 1



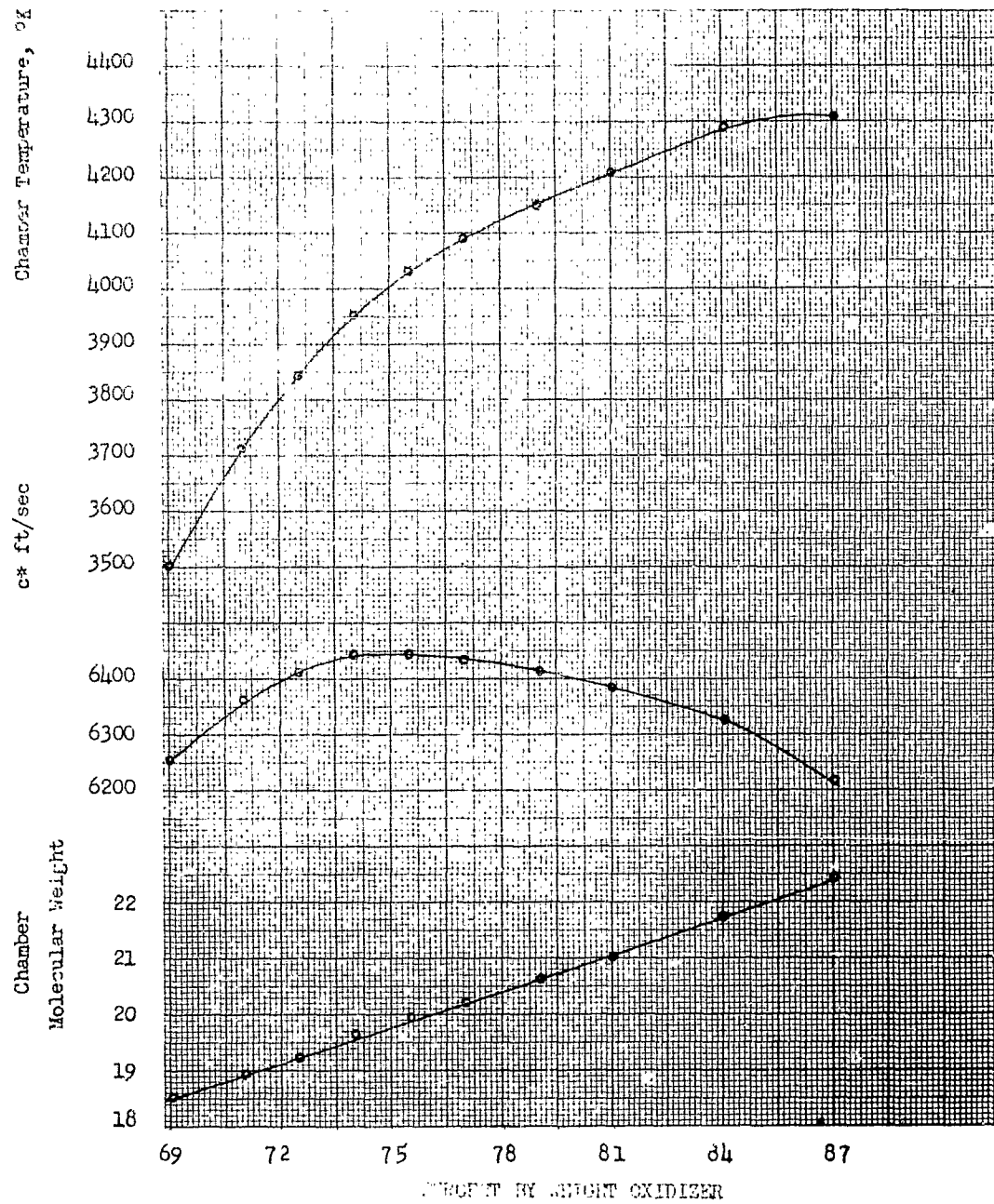
LITHIUM HYDRIDE - LITHIUM PERCHLORATE PERFORMANCE CURVES FIGURE 247

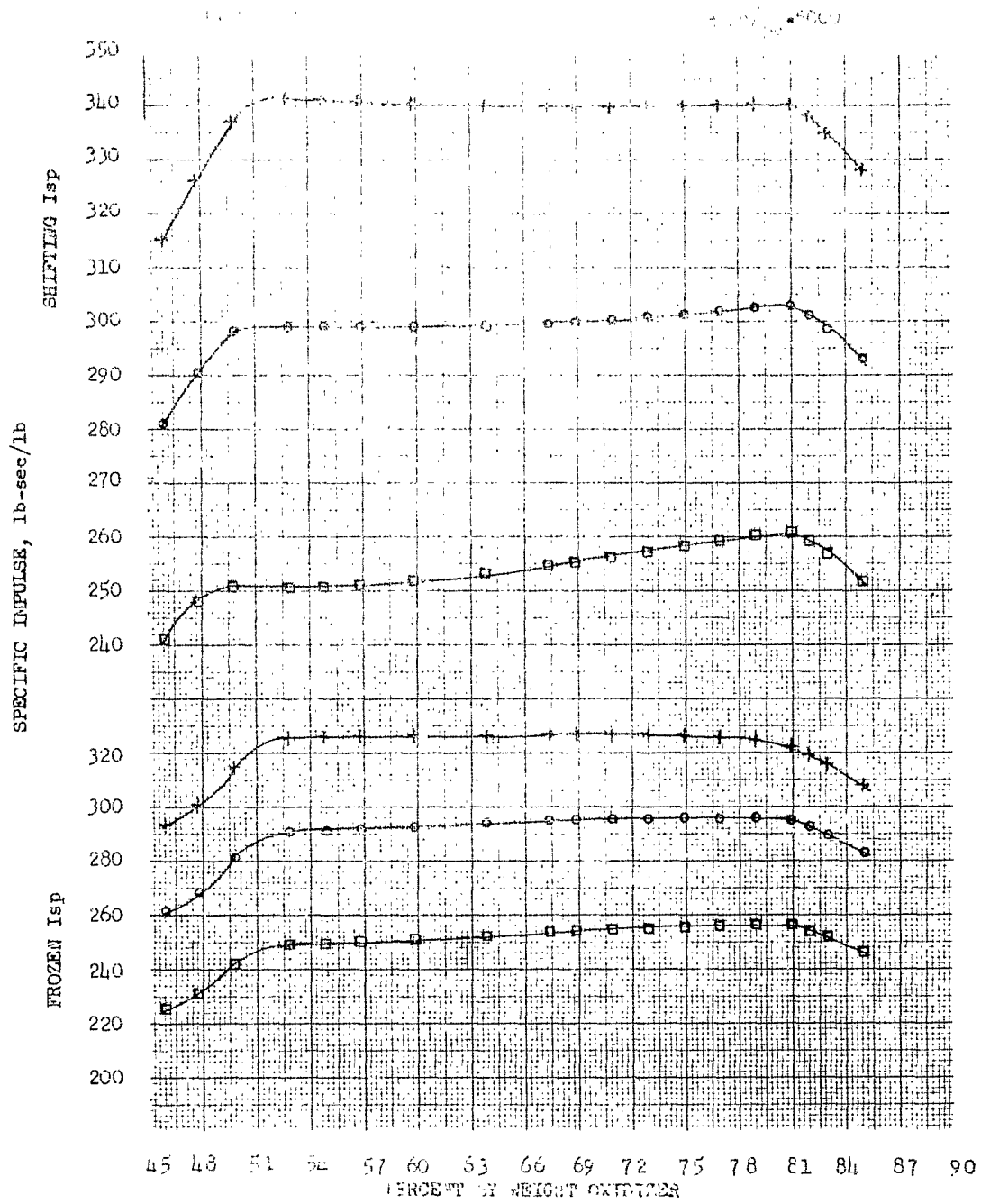


1-1110 - OXIDIZER - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 248



HYDROGEN PEROXIDE - HYDROGEN DIOXIDE PERFORMANCE CURVES FIGURE 249





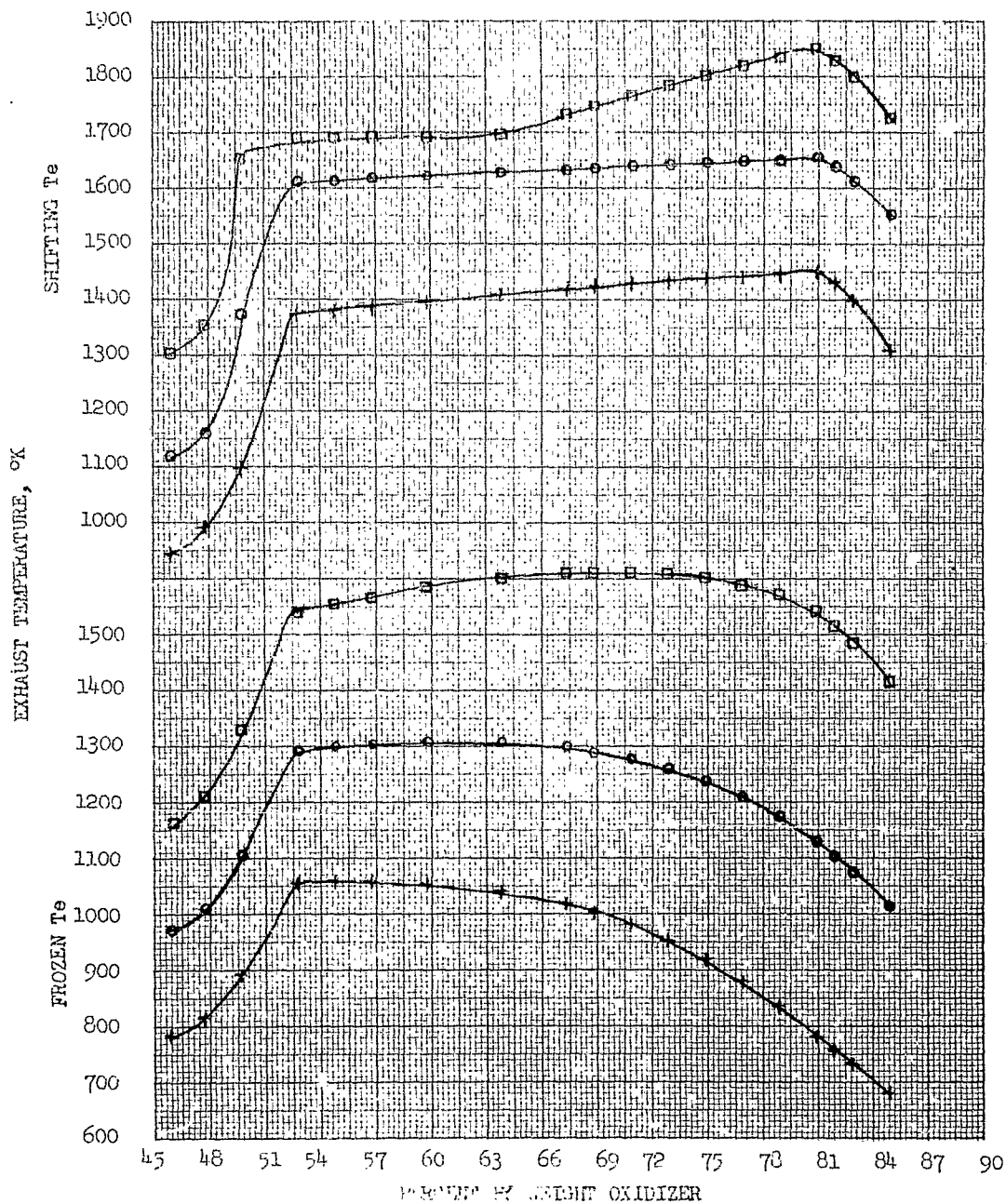
LITHIUM HYDRIDE - HYDROGEN PEROXIDE POLYMERIZATION CURVES FIGURE 251

1. 100/1

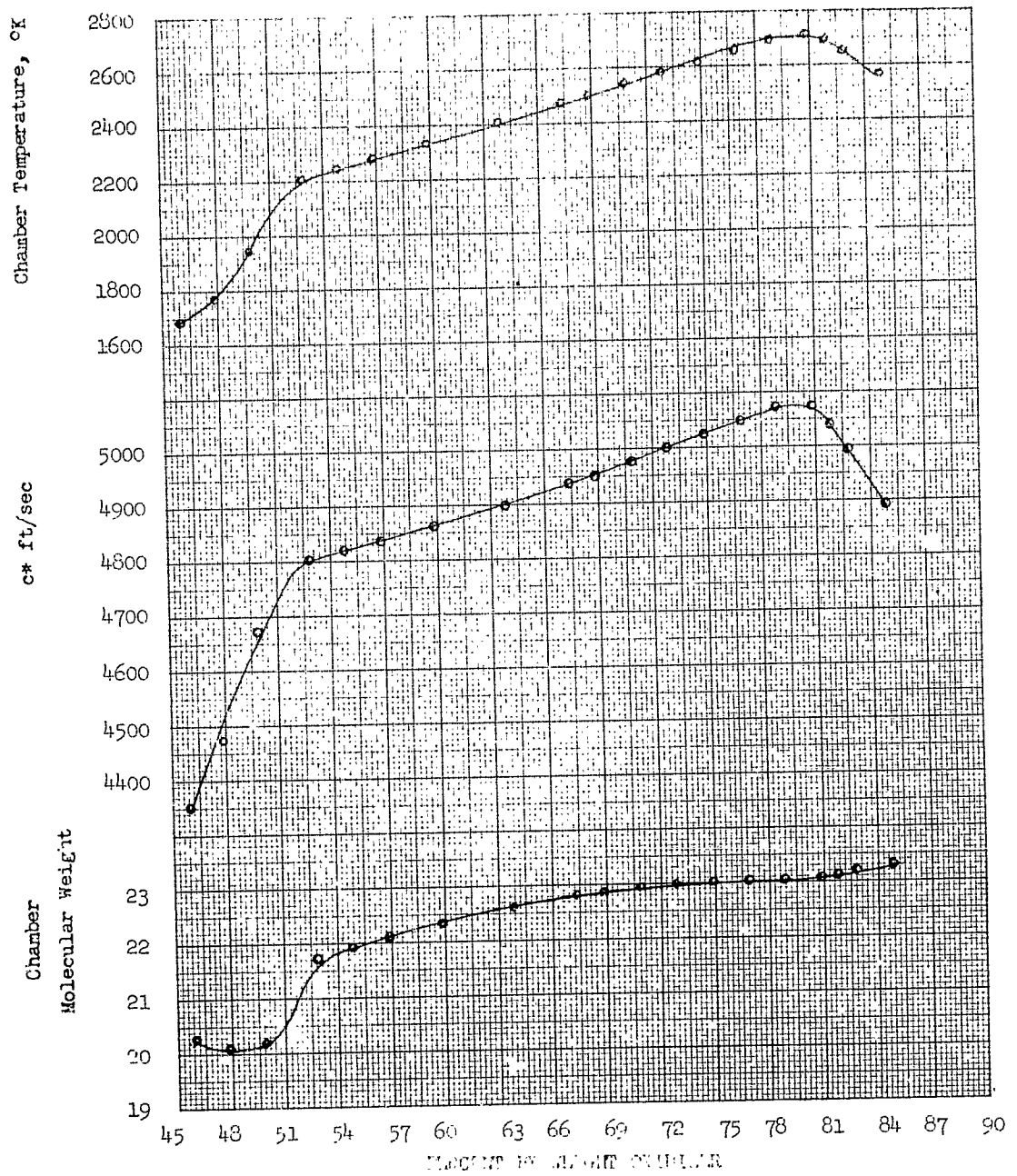
1. 100/1

1. 100/1

1. 100/1



LITHIUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 252



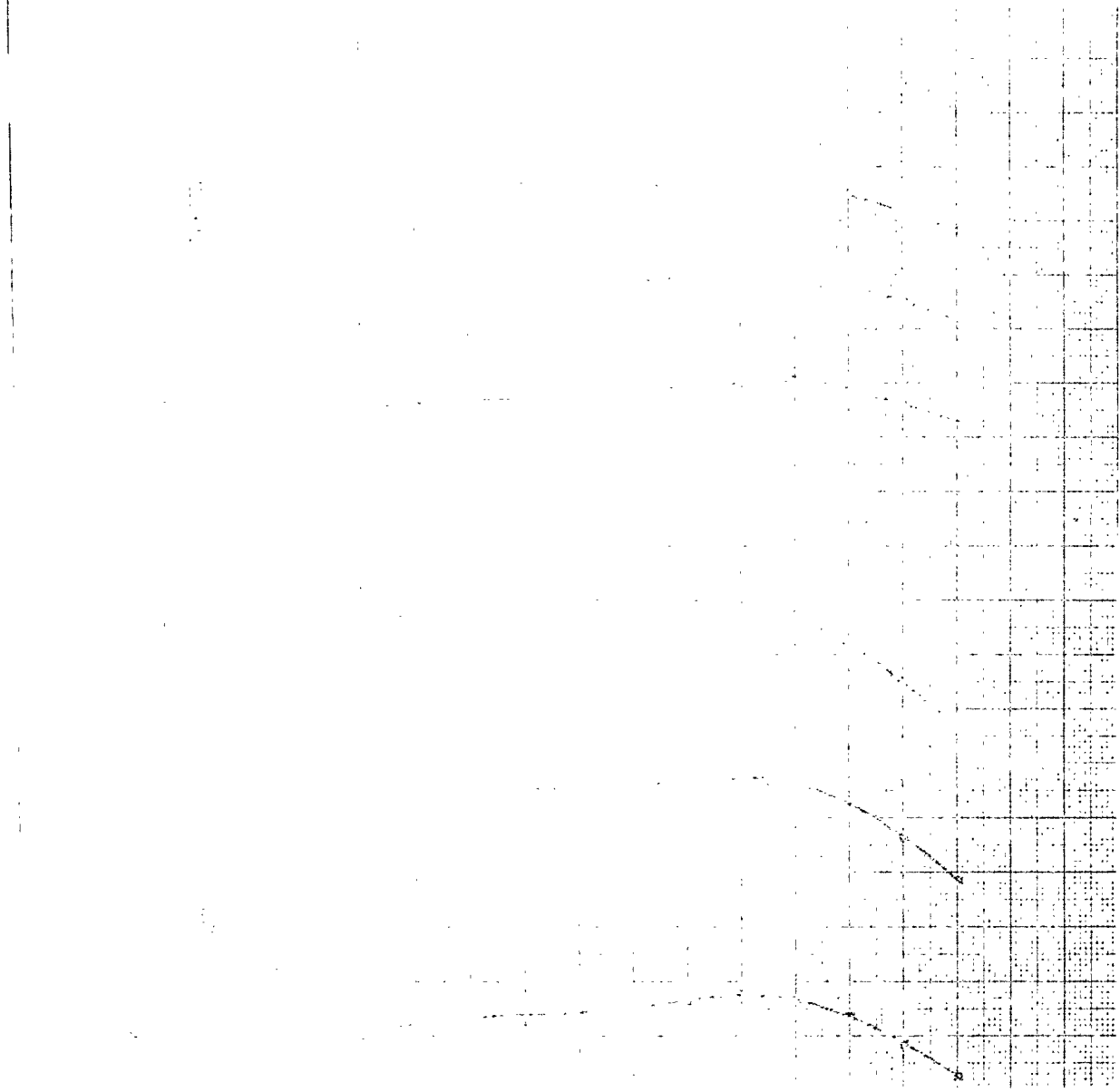
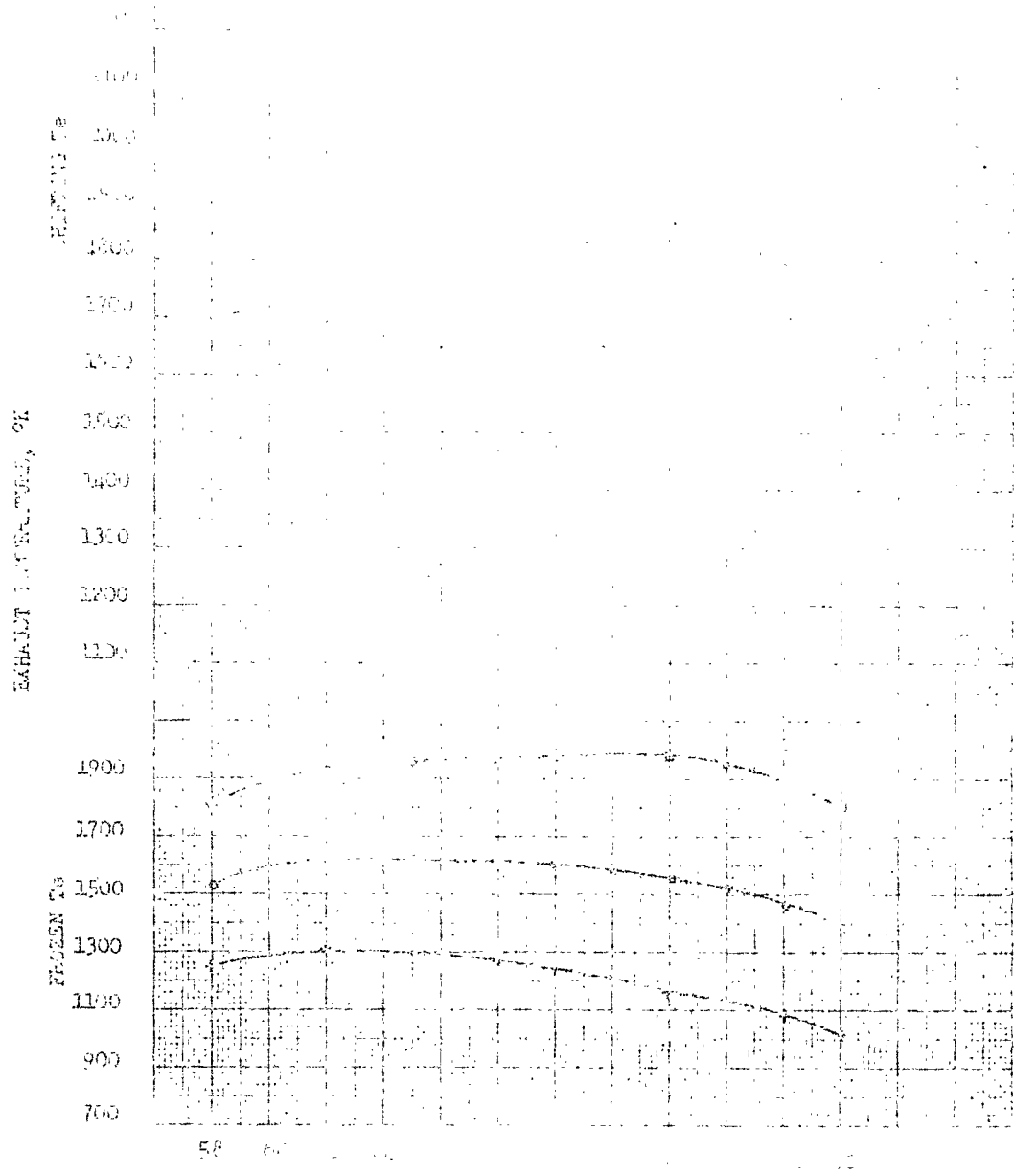
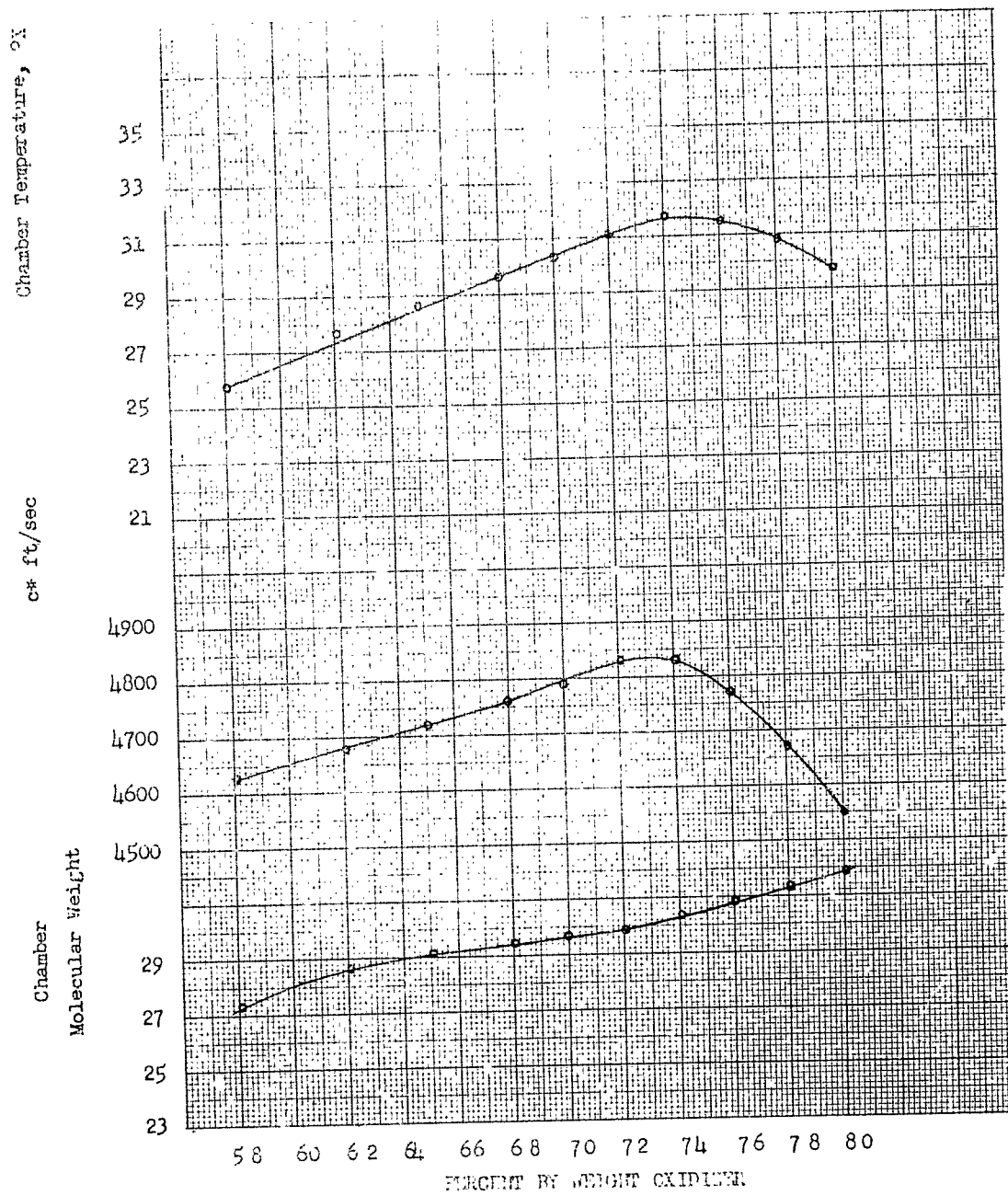


Figure 1. A graph showing the relationship between the variables x and y. The curves are labeled with letters from 'a' to 'z'.





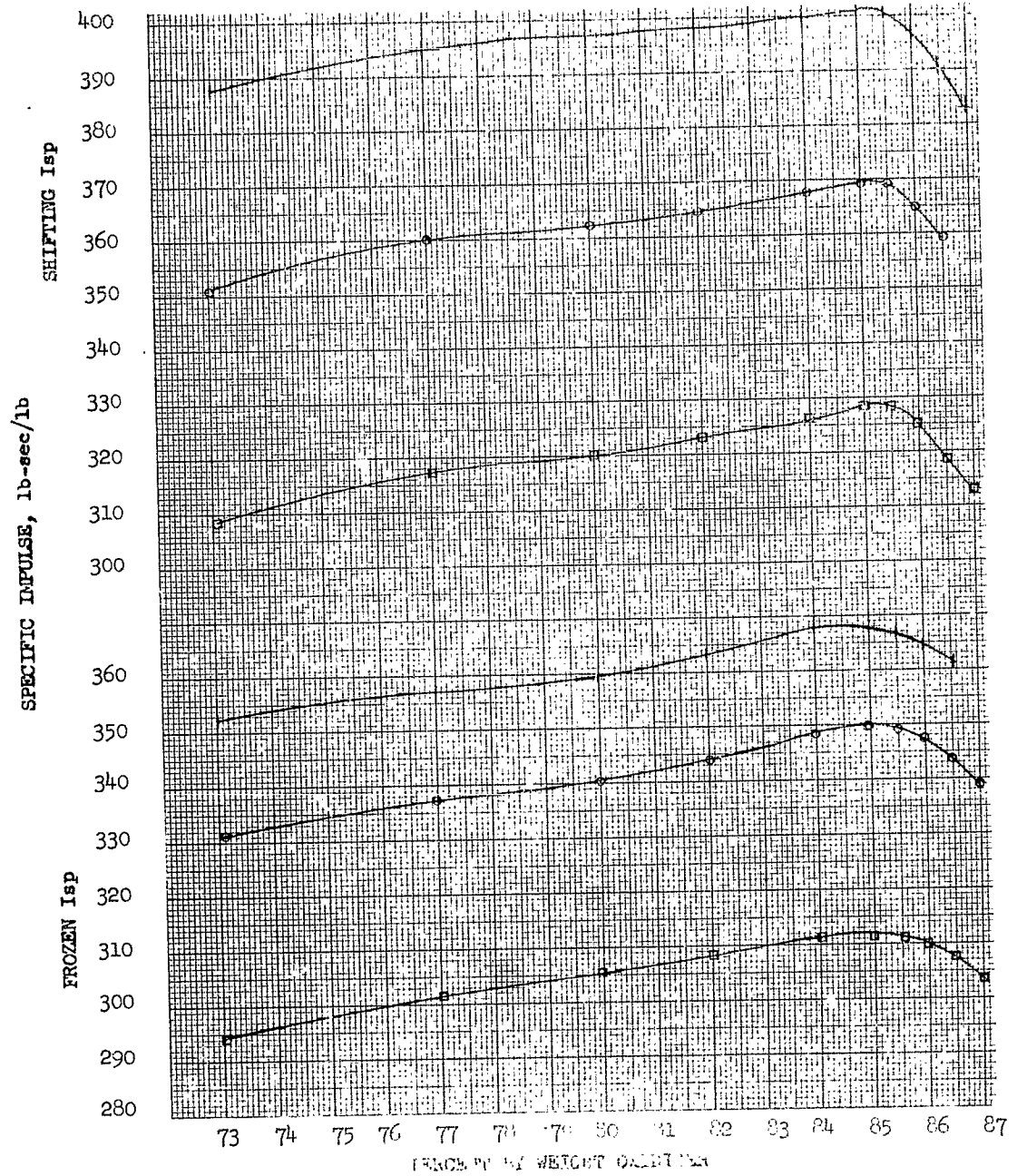
LITHIUM HYDRIDE - NEPTUNYL TRIFLUORIDE LEADFORMING CURVES FIGURE 97b

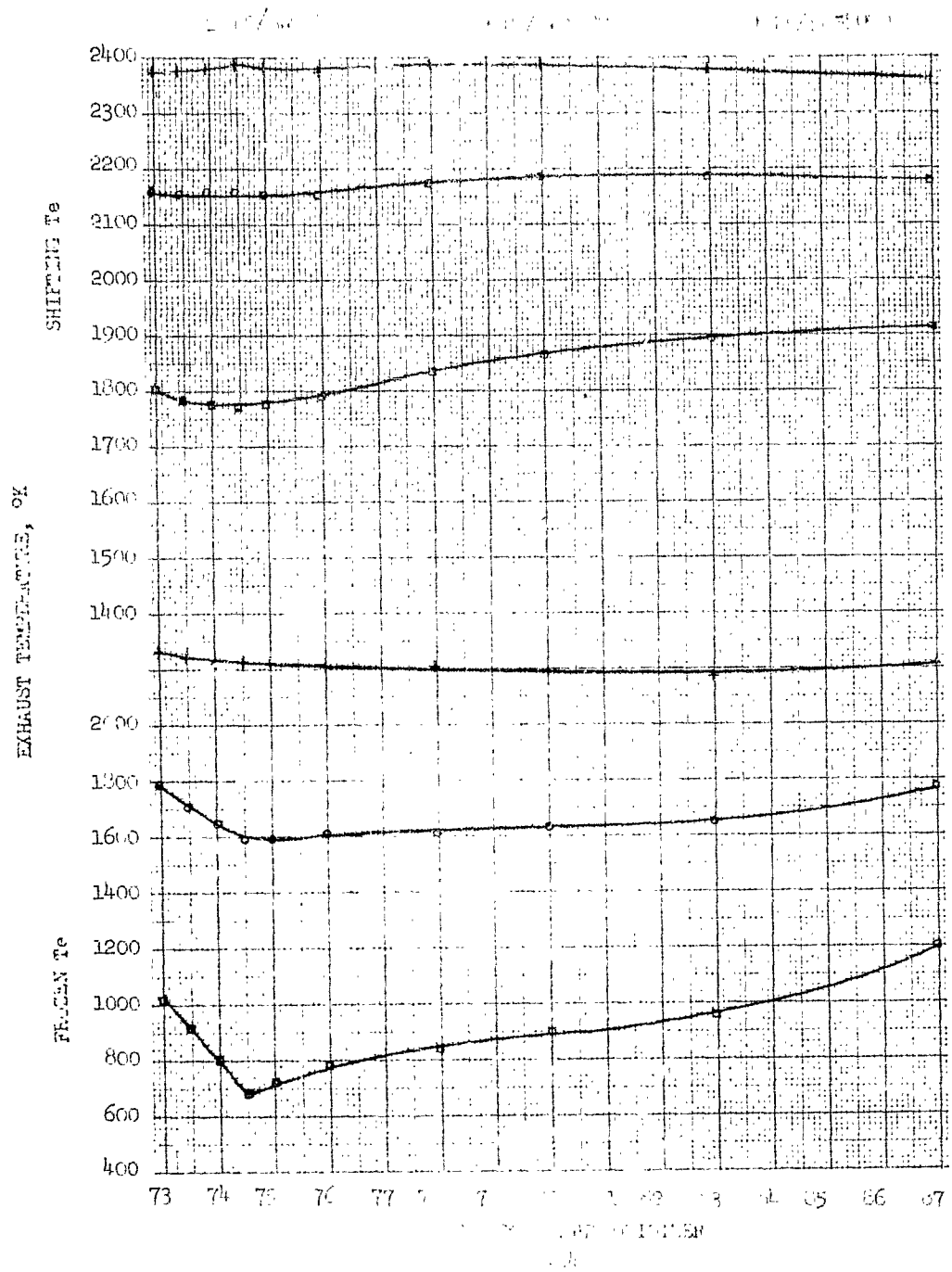
pc = 1000 psi

□ pc/p₀ = 0.8

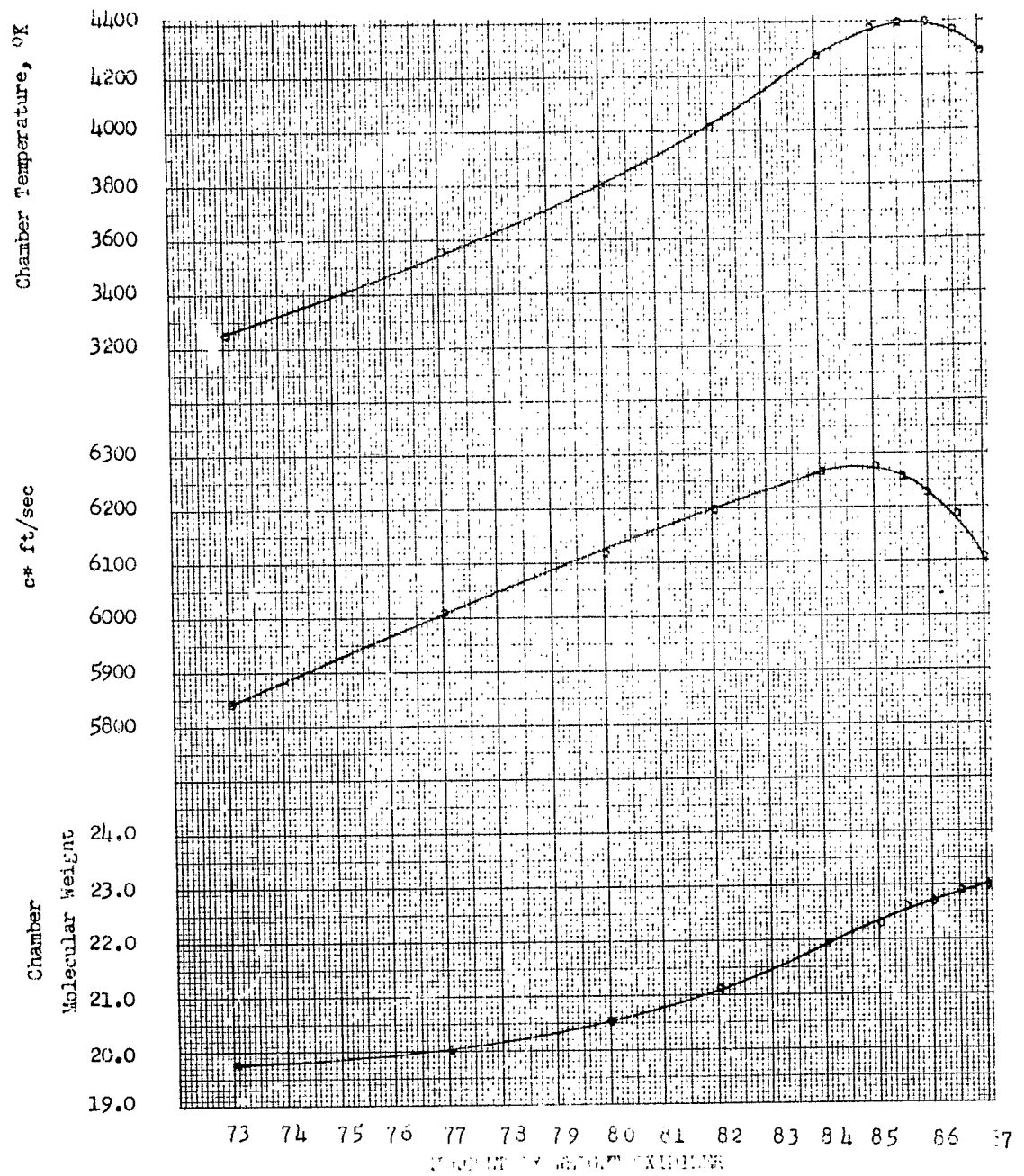
○ pc/p₀ = 0.500

+ pc/p₀ = 0.5000





LITHIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 258



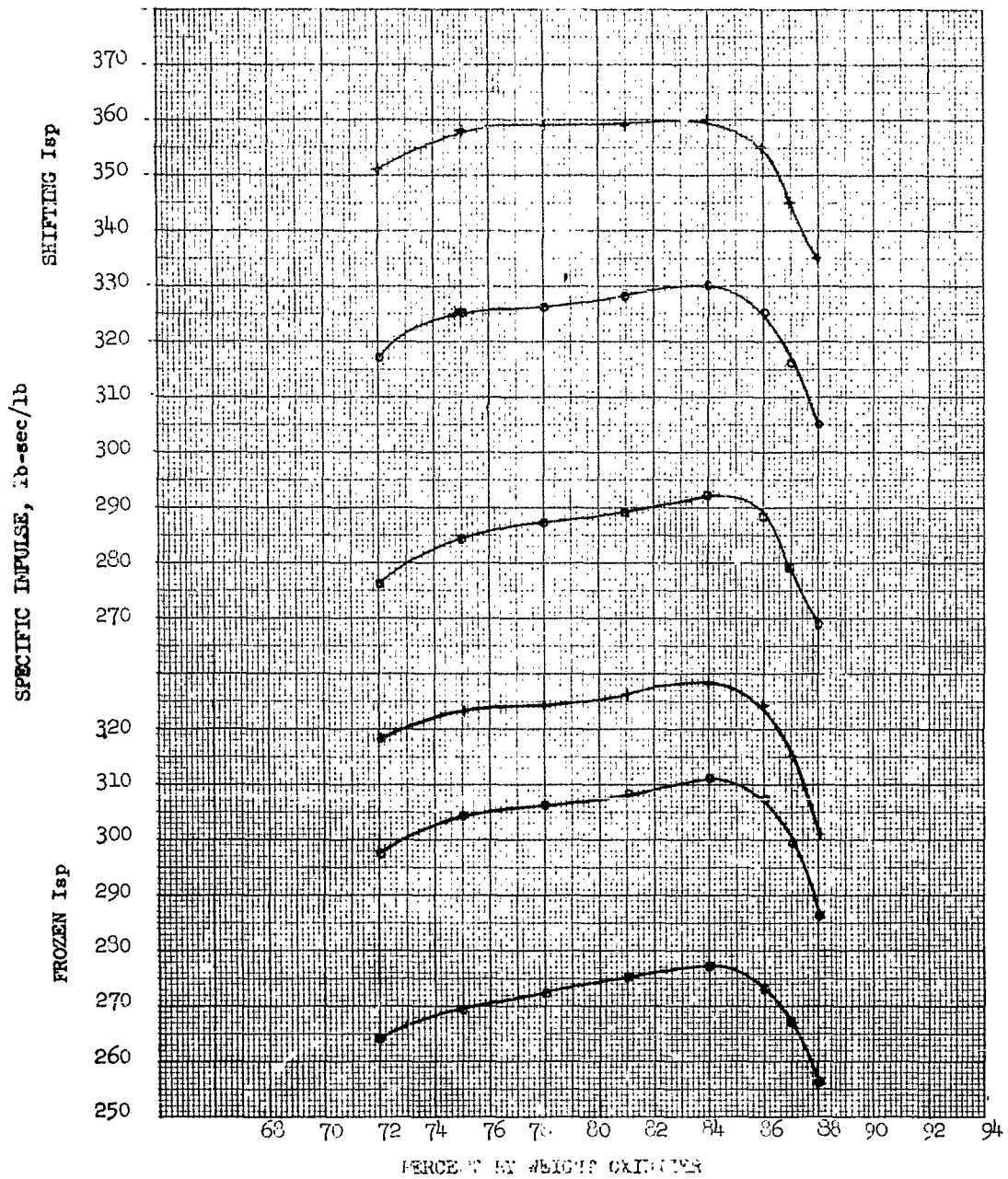
LITHIUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 229

$p_c = 1000 \text{ psf}$

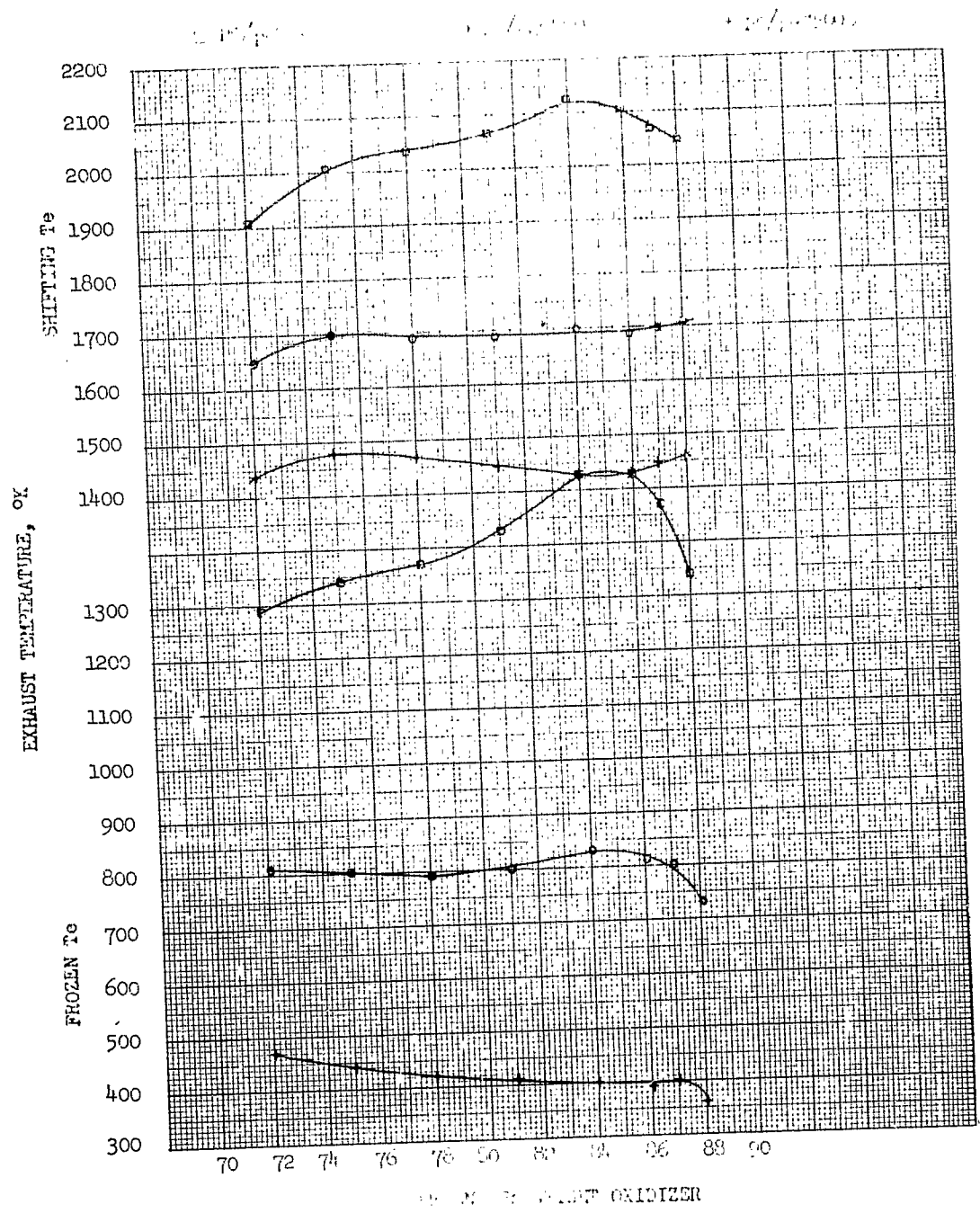
$\square \text{ } p_c/p_c = 700$

$\circ \text{ } p_c/p_c = 4500$

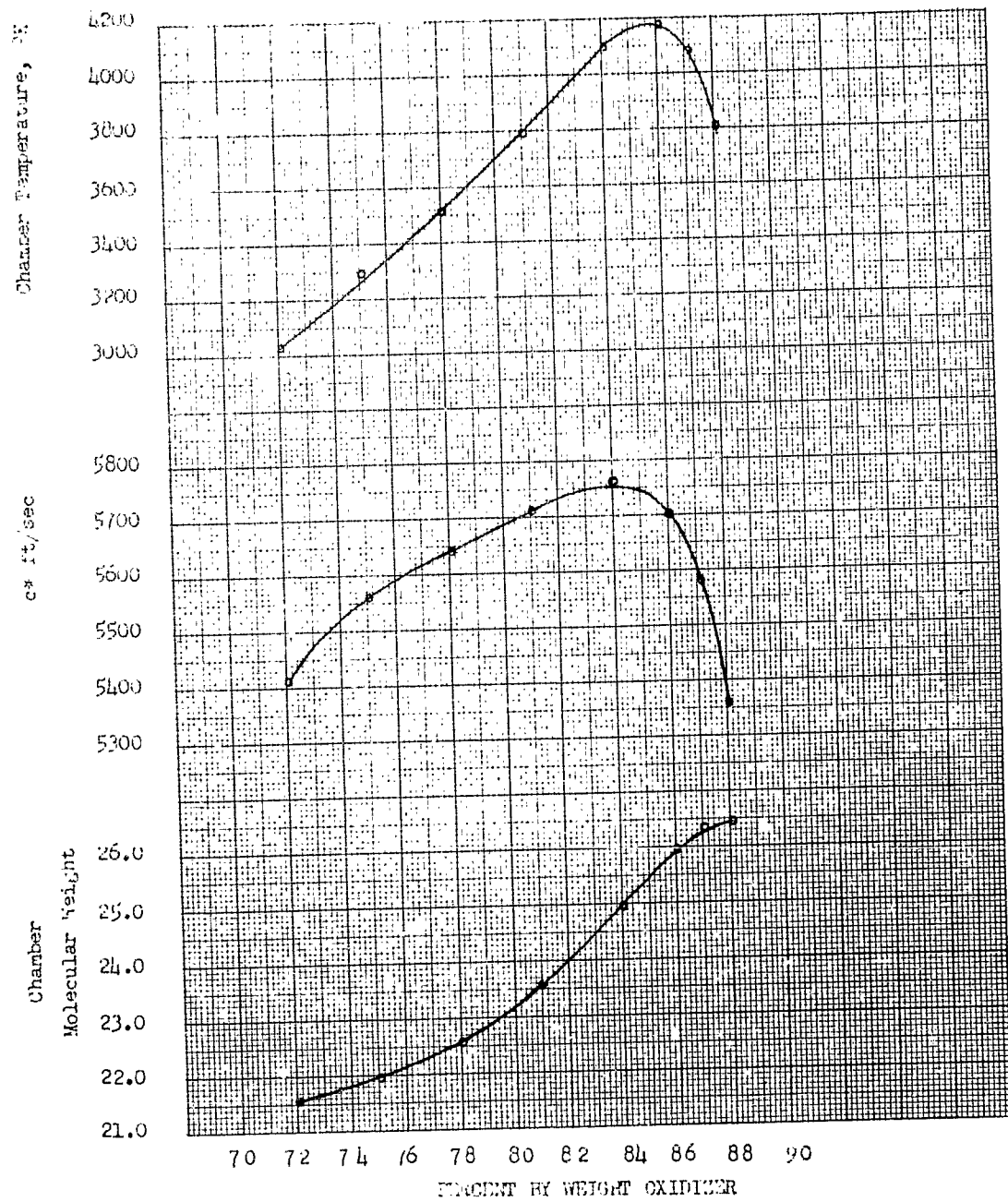
$+ \text{ } p_c/p_c = 5000$



LITHIUM HYDRIDE - CHLORINE BY DIFFERENTIAL SCANNING CALORIMETRY (DSC) FIGURE 107

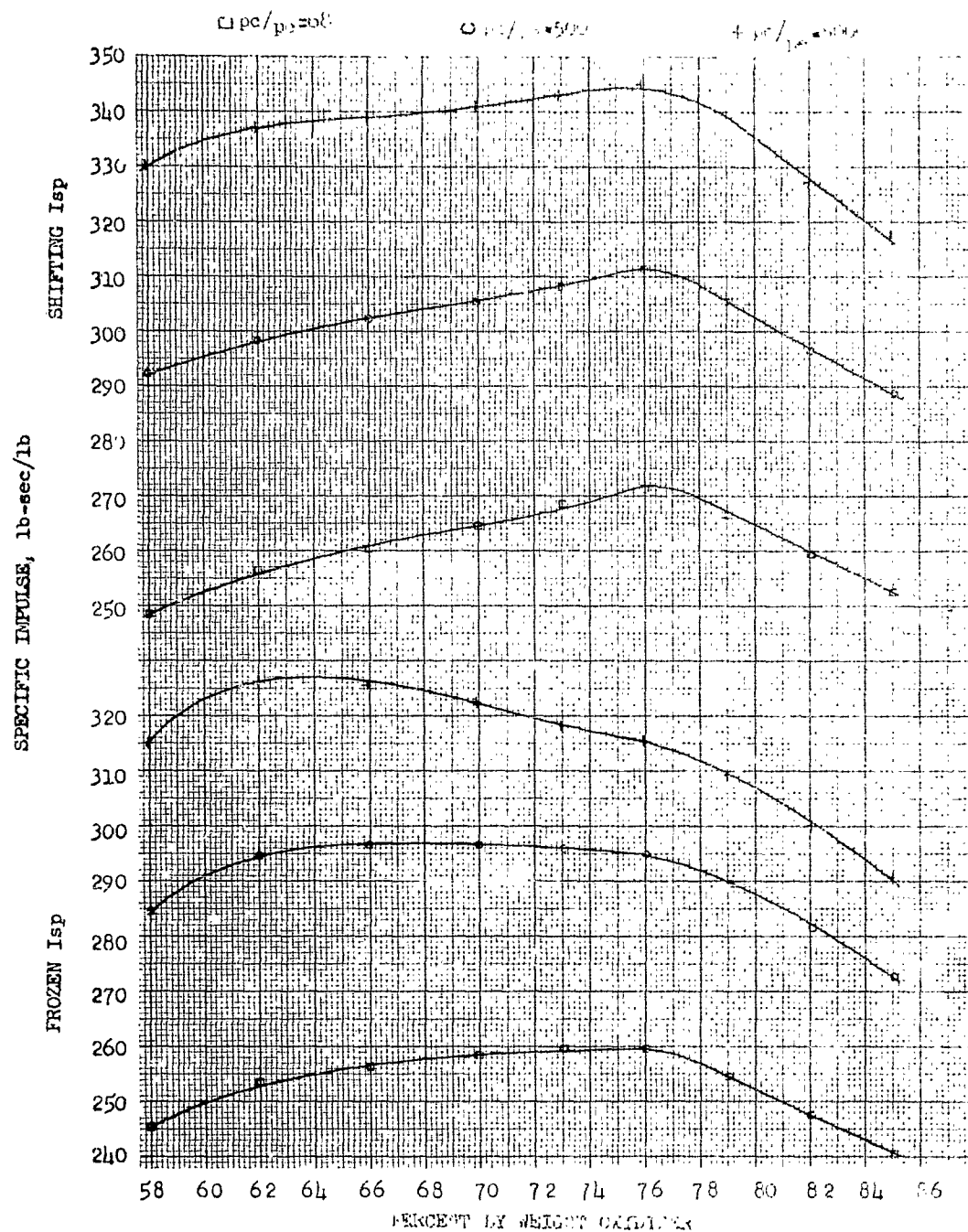


HYPERGOL - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 261

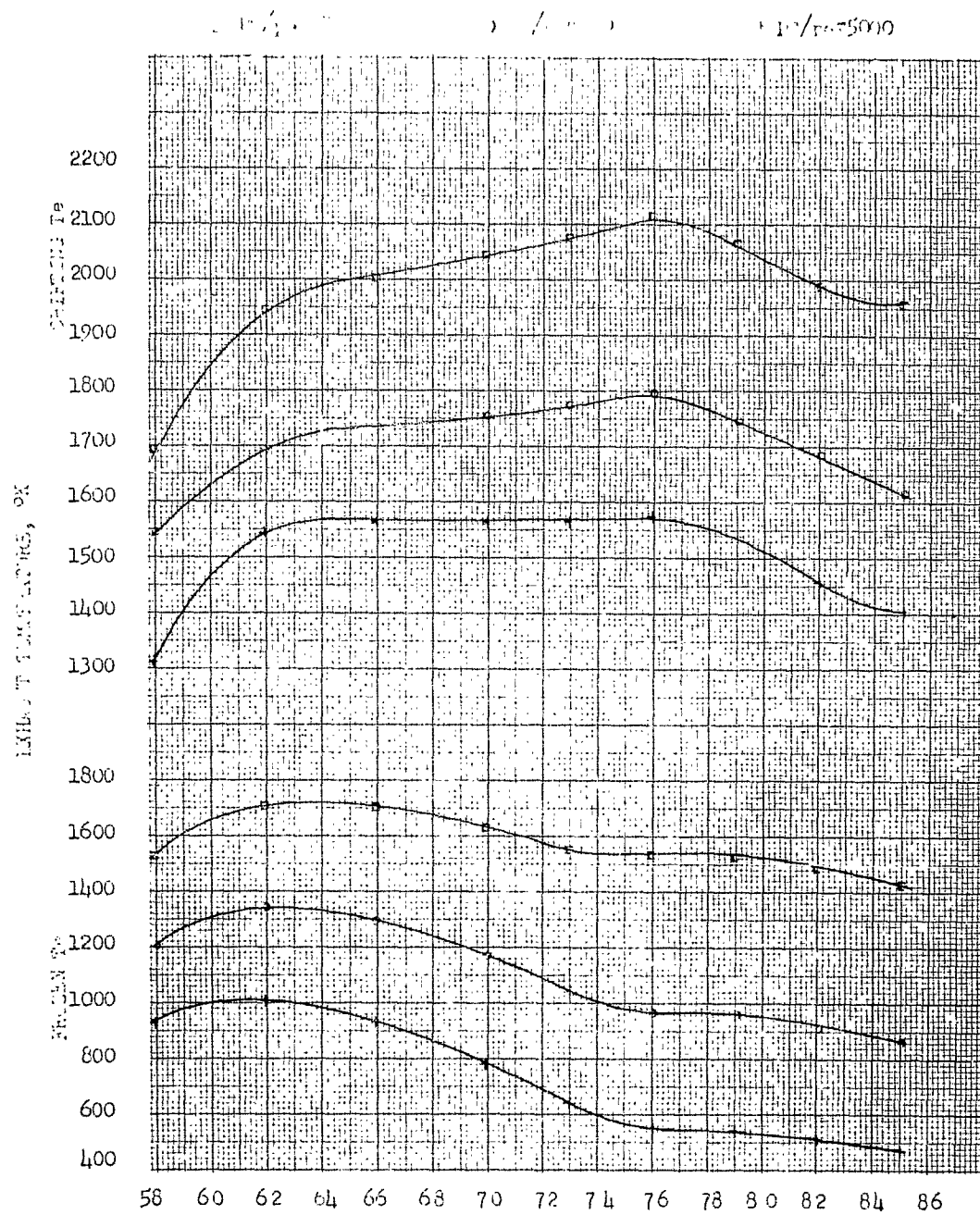


LITHIUM HYDRIDE - PERCHLORYL ALUMINATE PERFORMANCE CURVES AT 3000 PSI

1000 gmi



LITHIUM HYDRIDE - PERCHLORATE FLUORIDE PERFORMANCE CURVES FIGURE 263



LITHIUM NITRIDE - PERCHLORATE FLUORIDE PERFORMANCE CURVES FIGURE 265

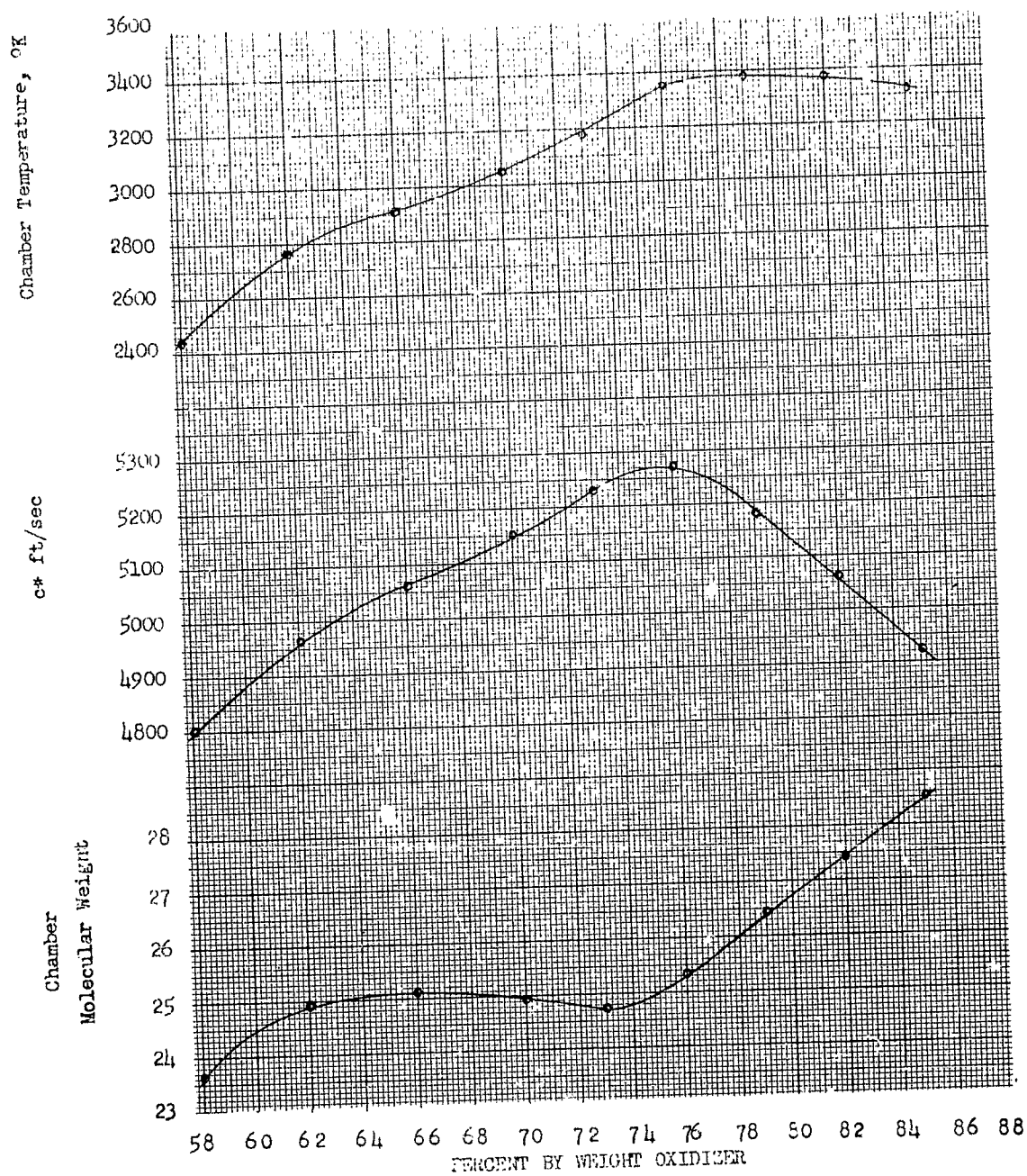
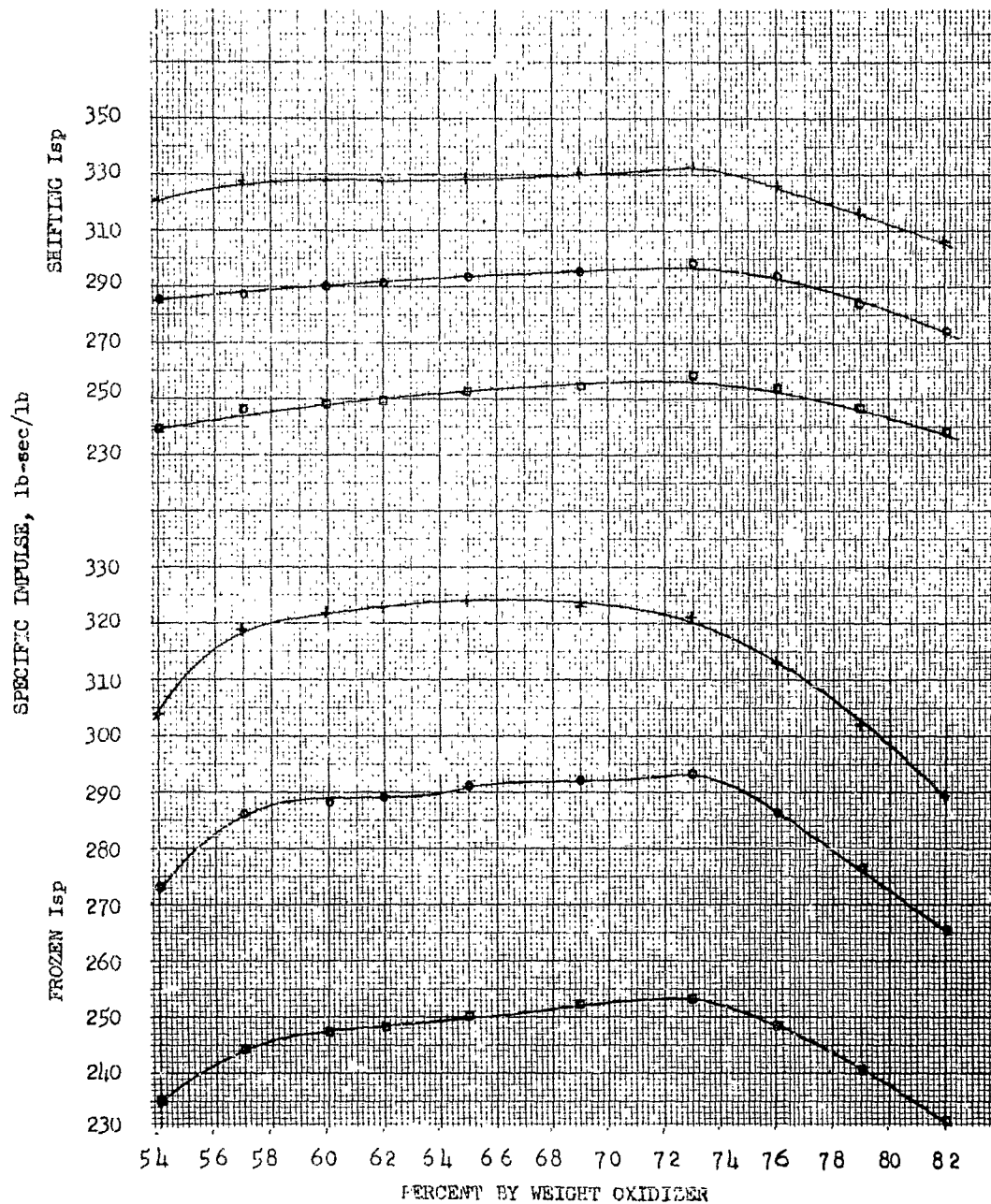


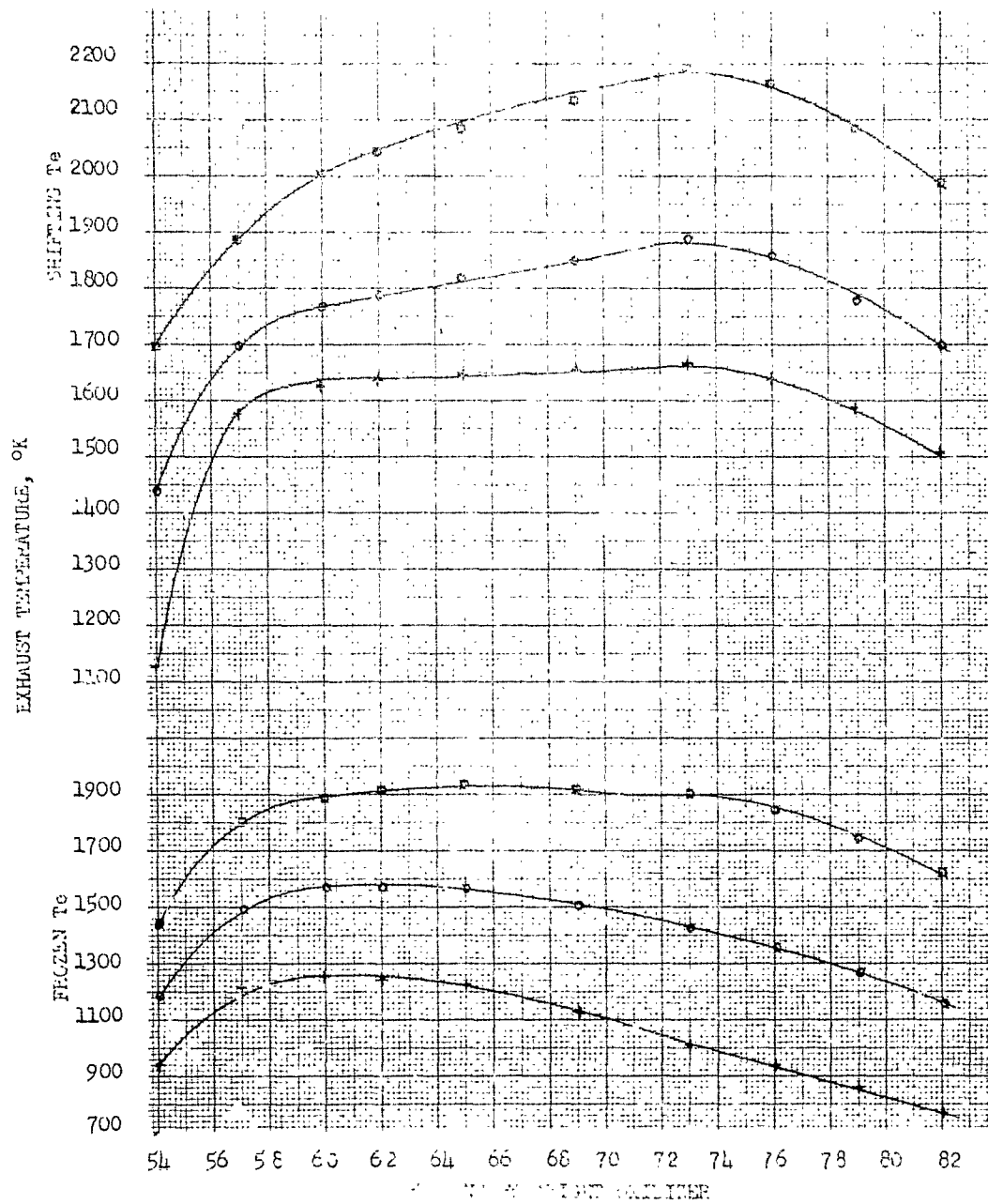
Figure 265

$\frac{p_{c1}}{p_e} = 3$

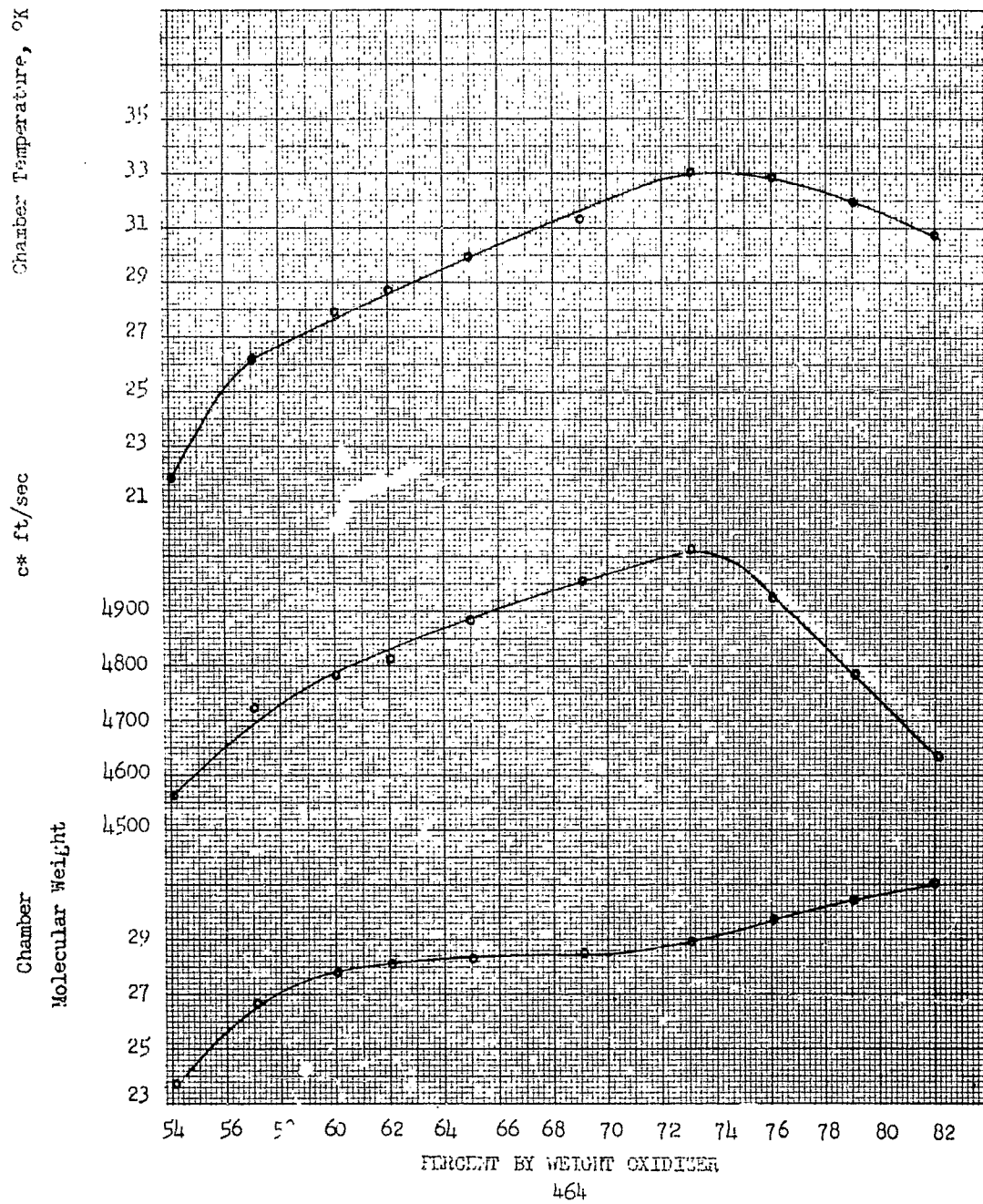
$\frac{p_{c1}}{p_e} = 500$

$\frac{p_{c1}}{p_e} = 5000$



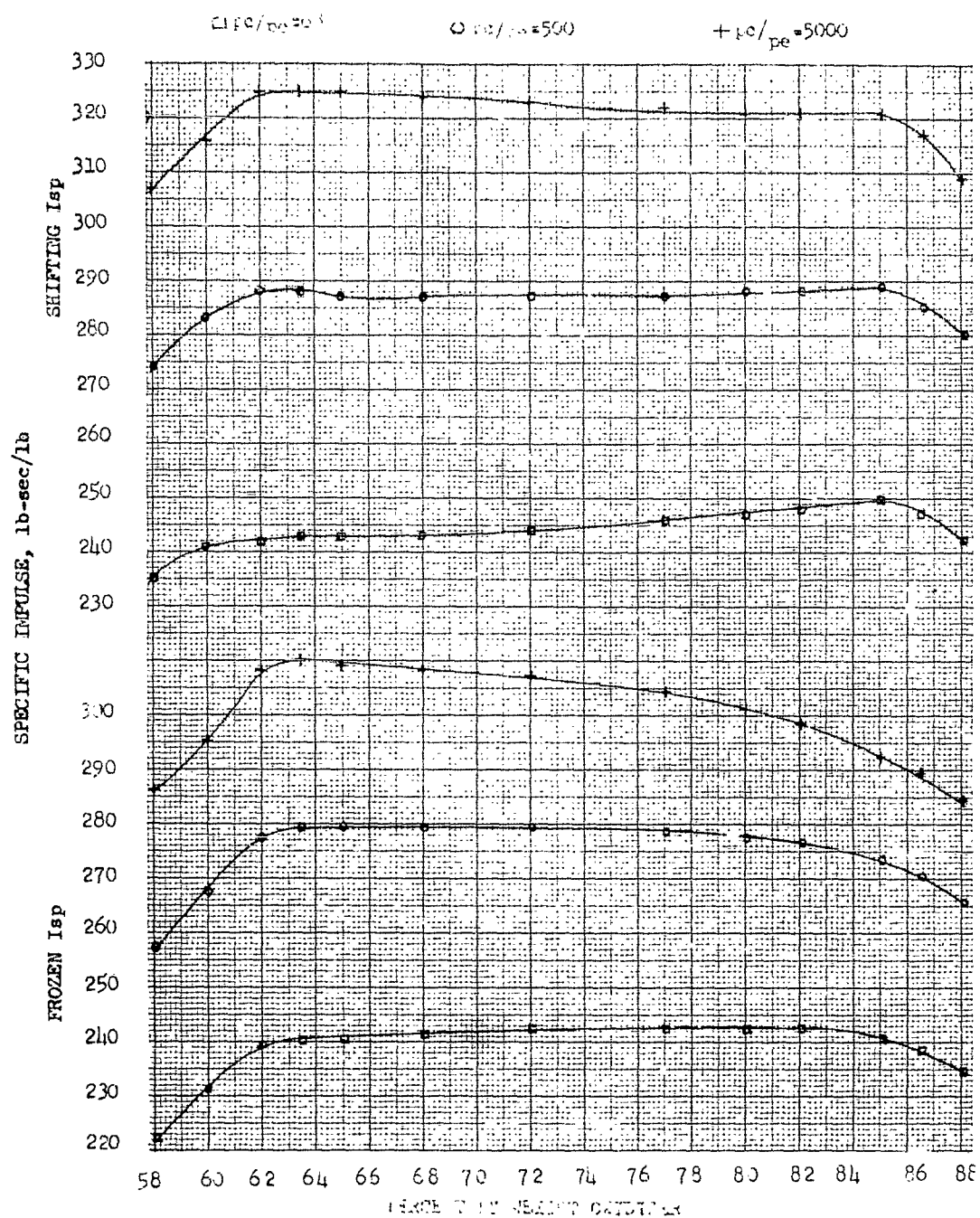


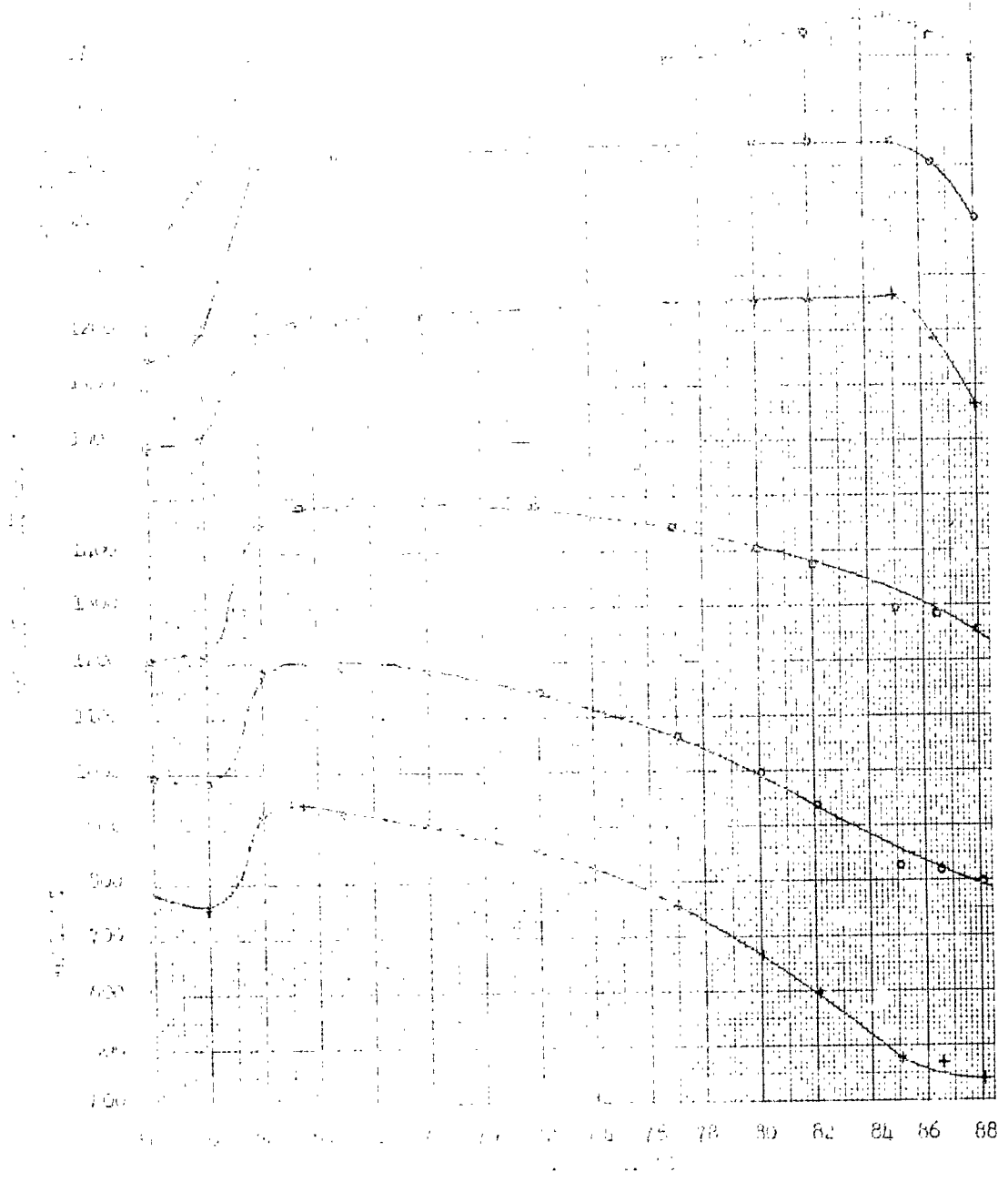
LITHIUM HYDRIDE - LITHIUM PHOSPHATE PERFORMANCE CURVES FIGURE 267

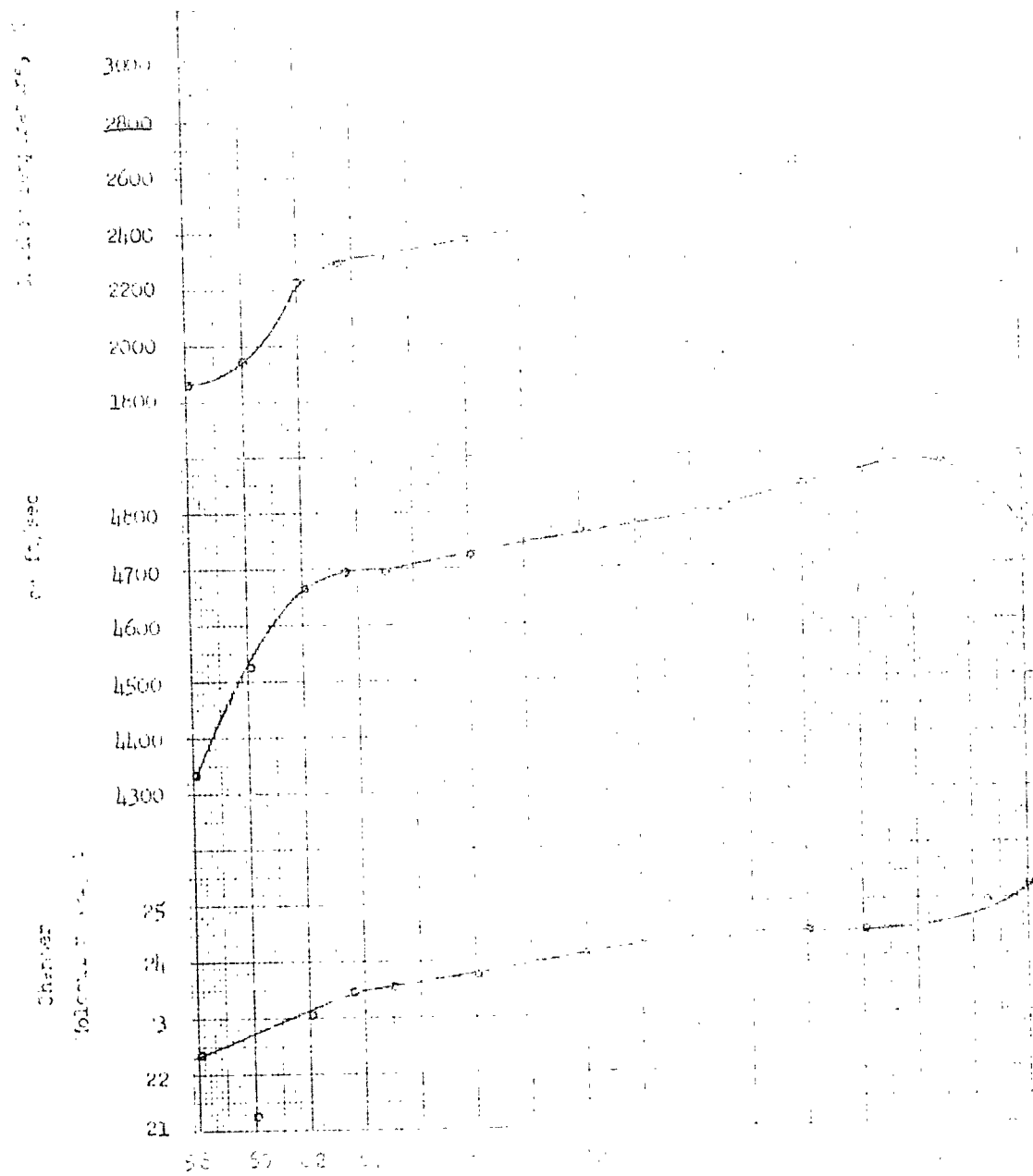


LITHIUM HYDRIDE - AMMONIUM PERCHLORATE ELECTRIC-ARC CATHODES FIGURE 268

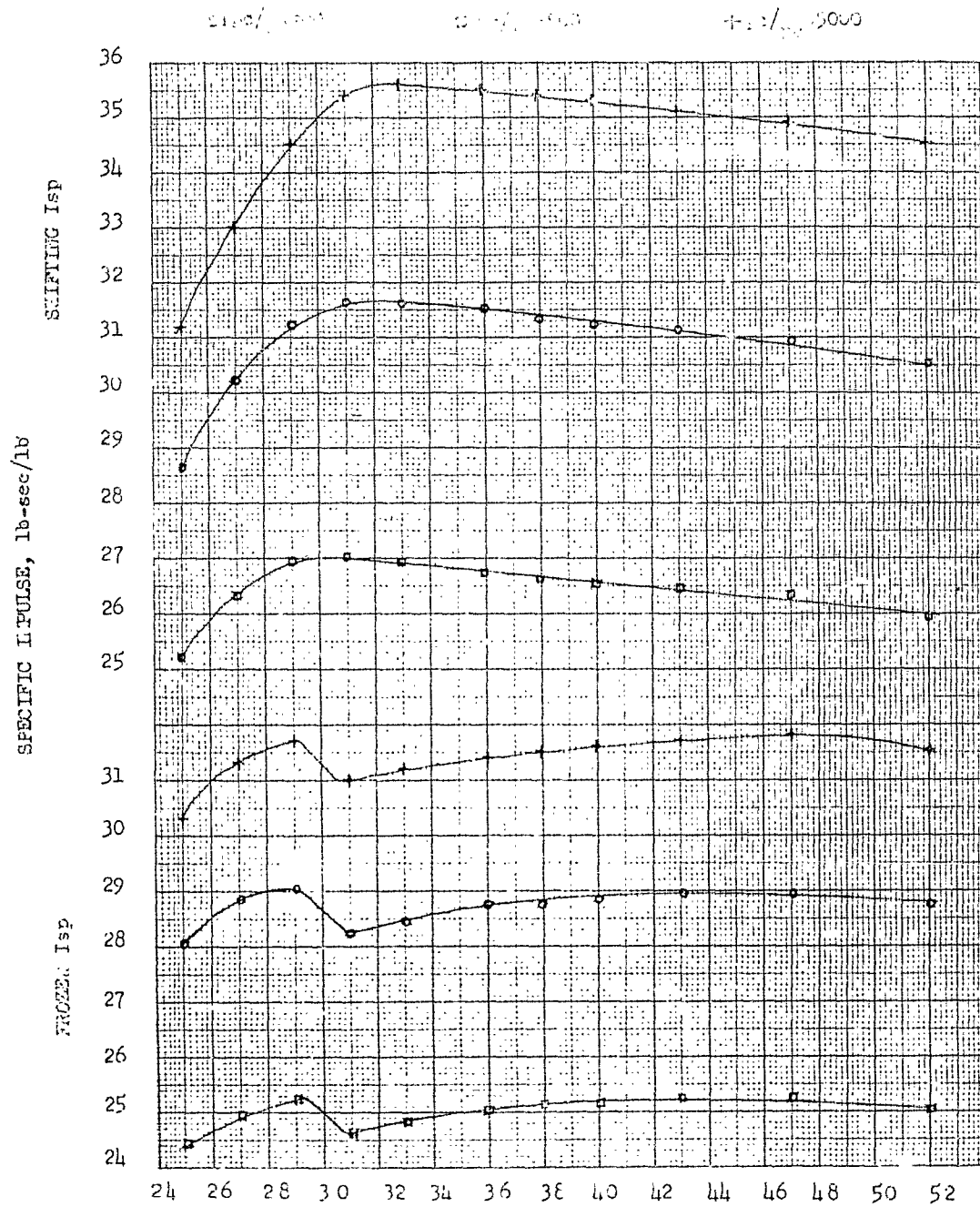
$t = 1000 \text{ psi}$







MAGNESIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 271



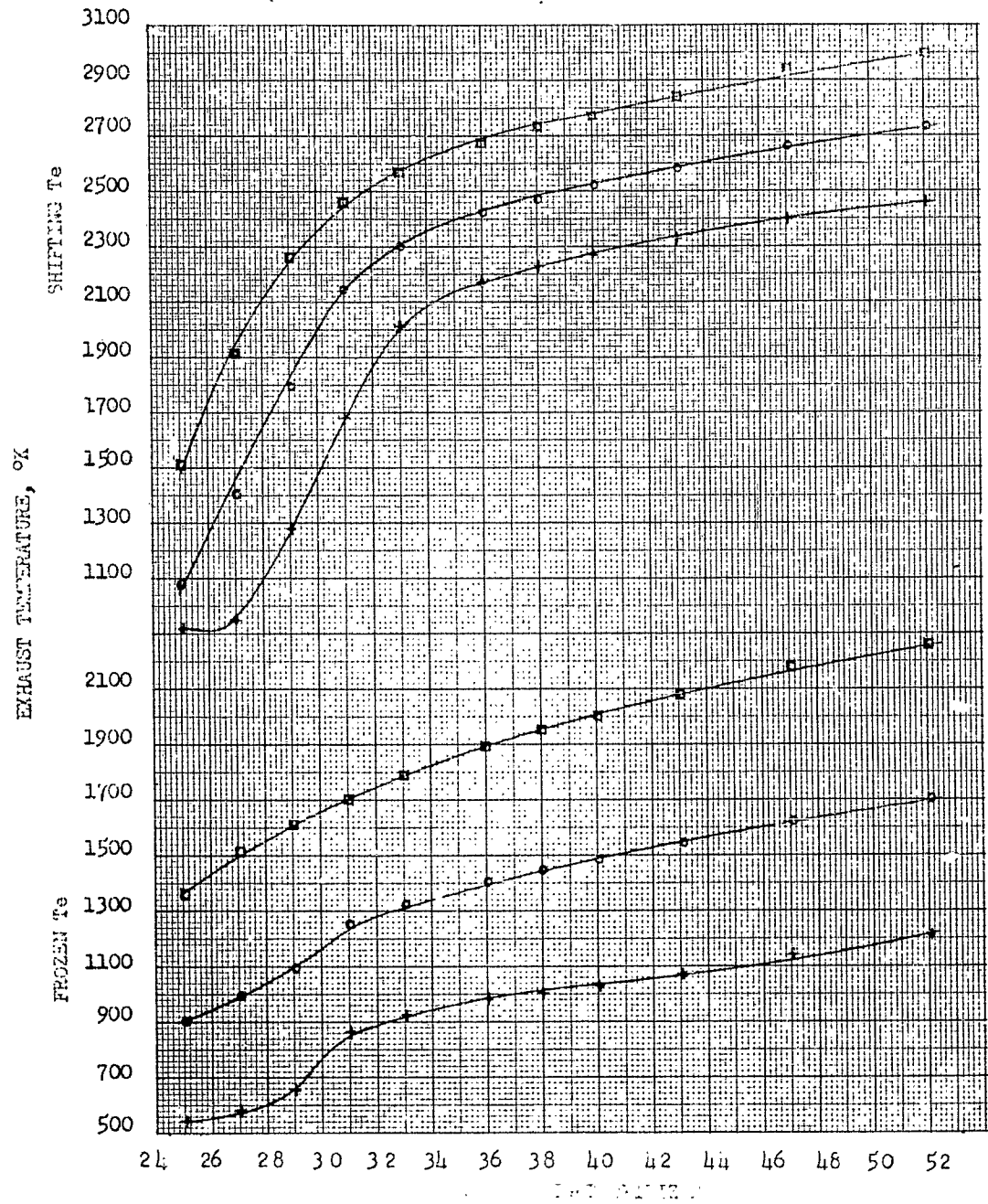
MAGNESIUM HYDRIDE - LIQUID OXYGEN PERFORMANCE CURVES FIGURE 272

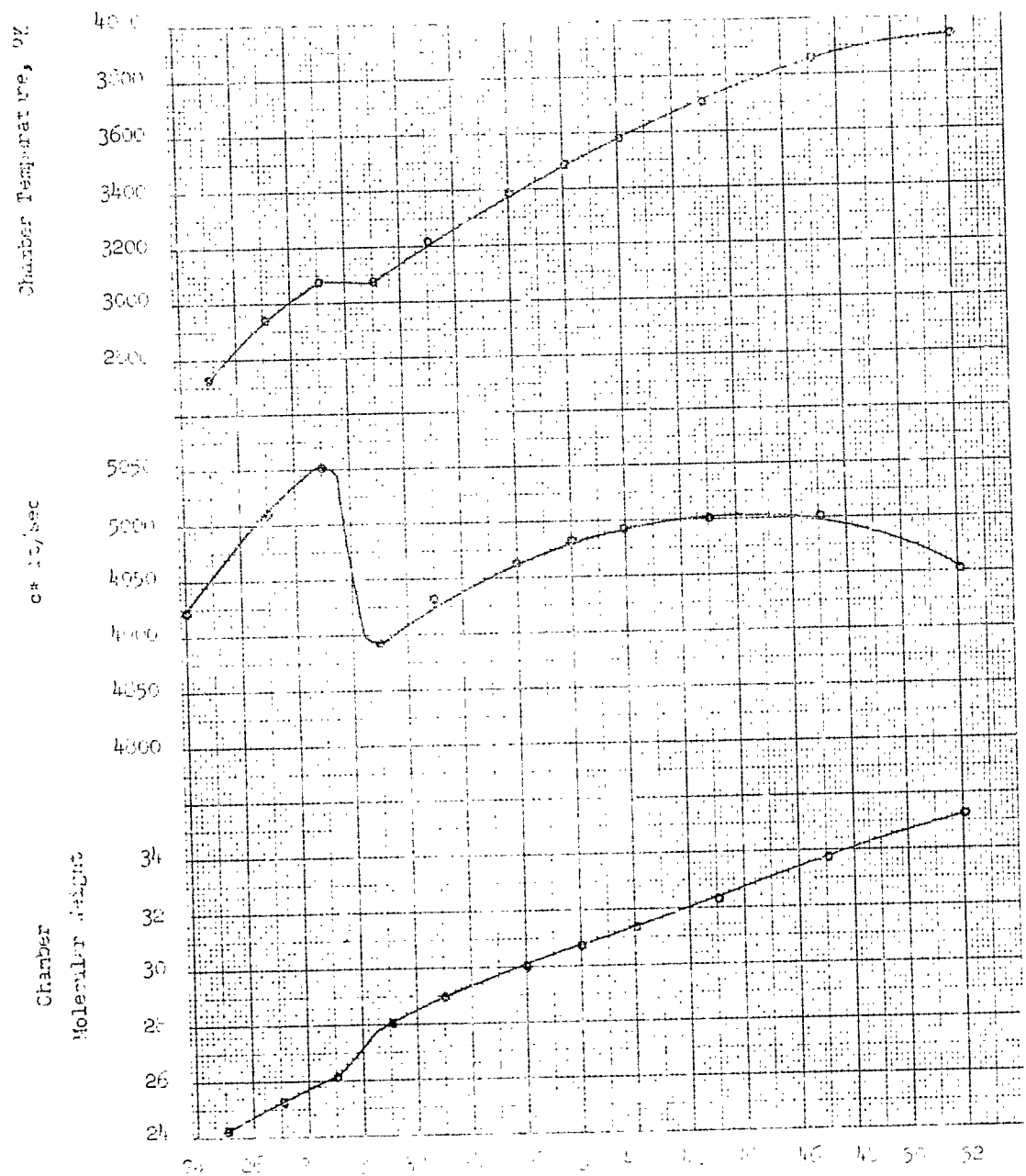
1000/1000

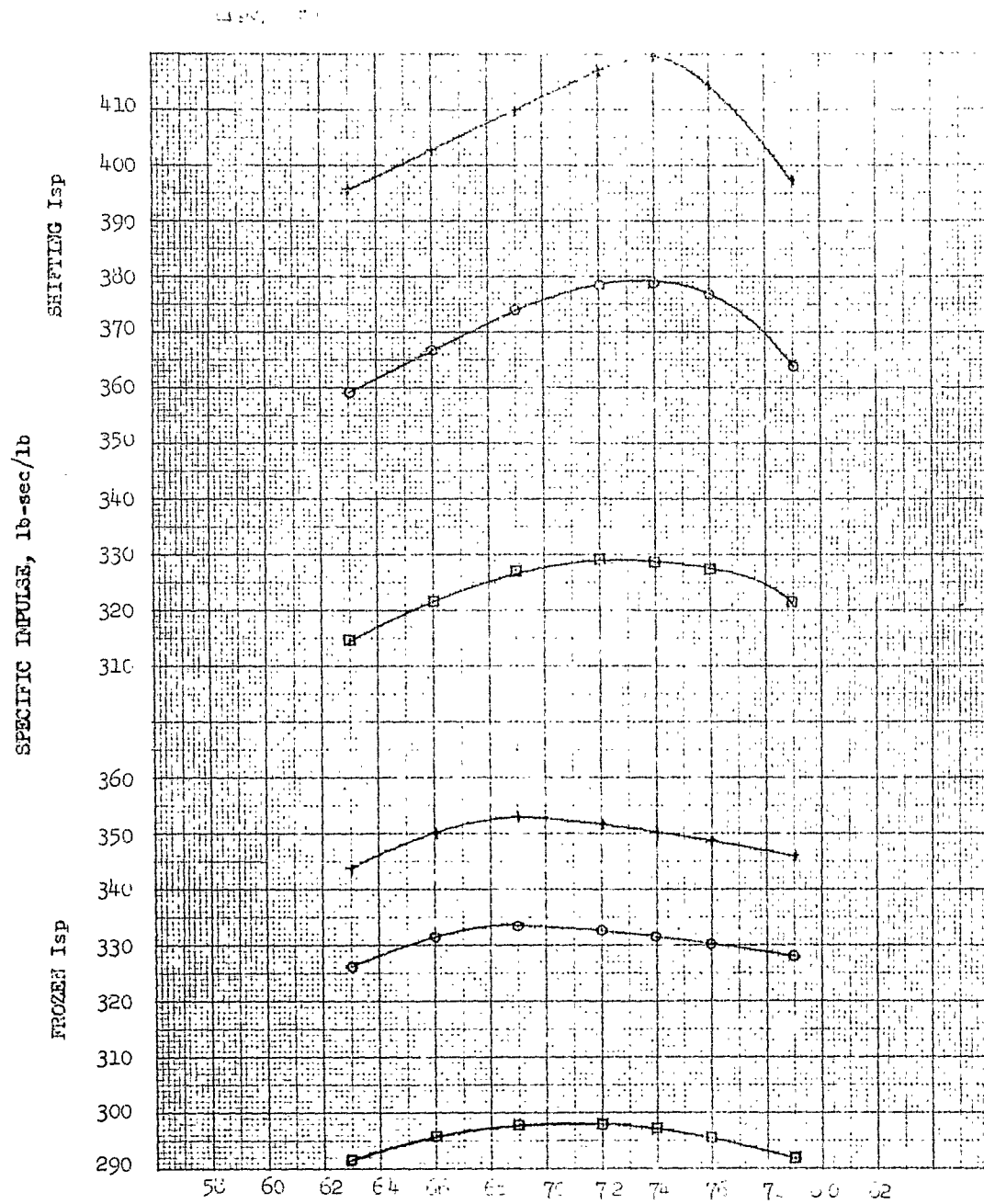
1000/1000

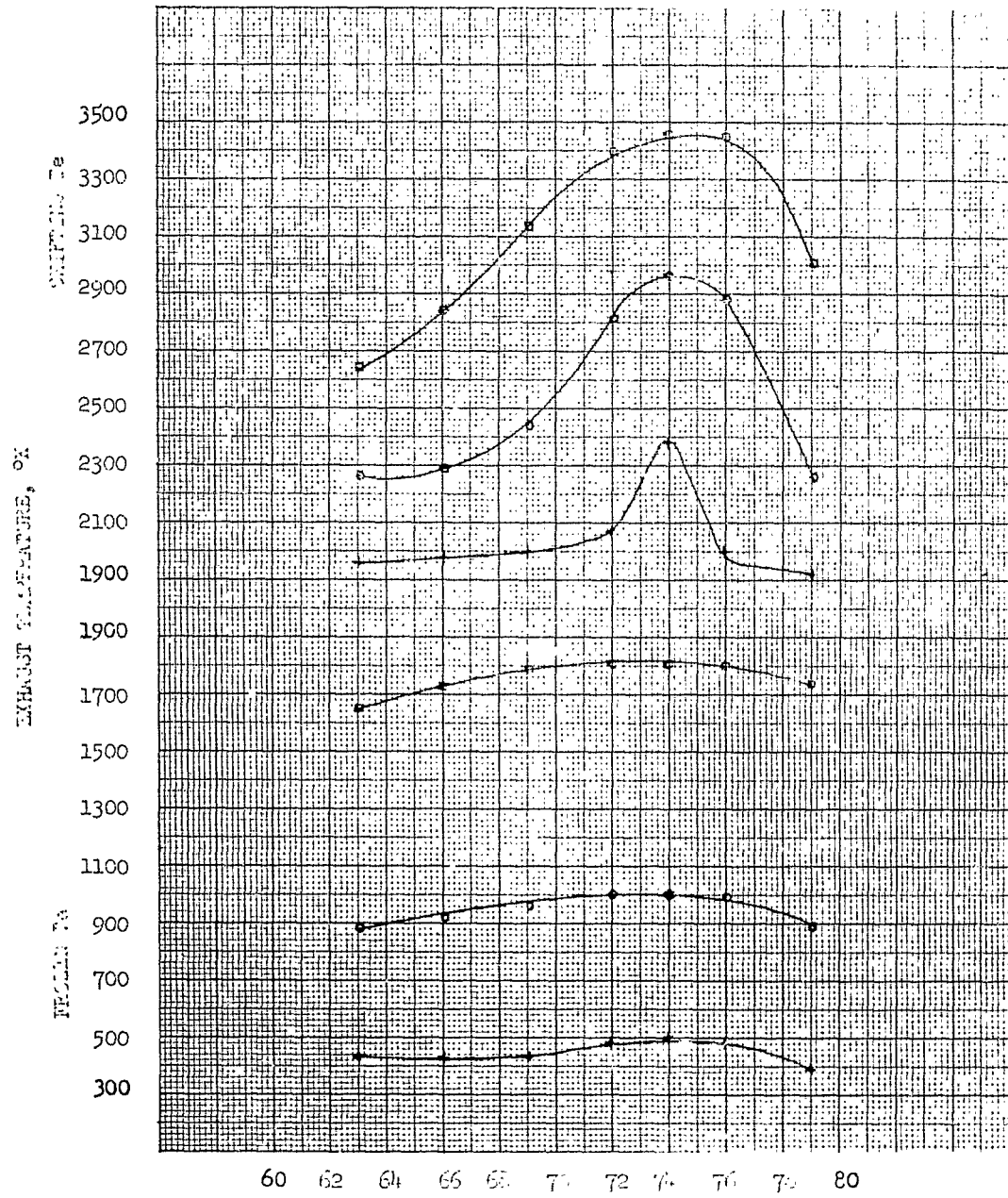
1000/1000

1000/1000

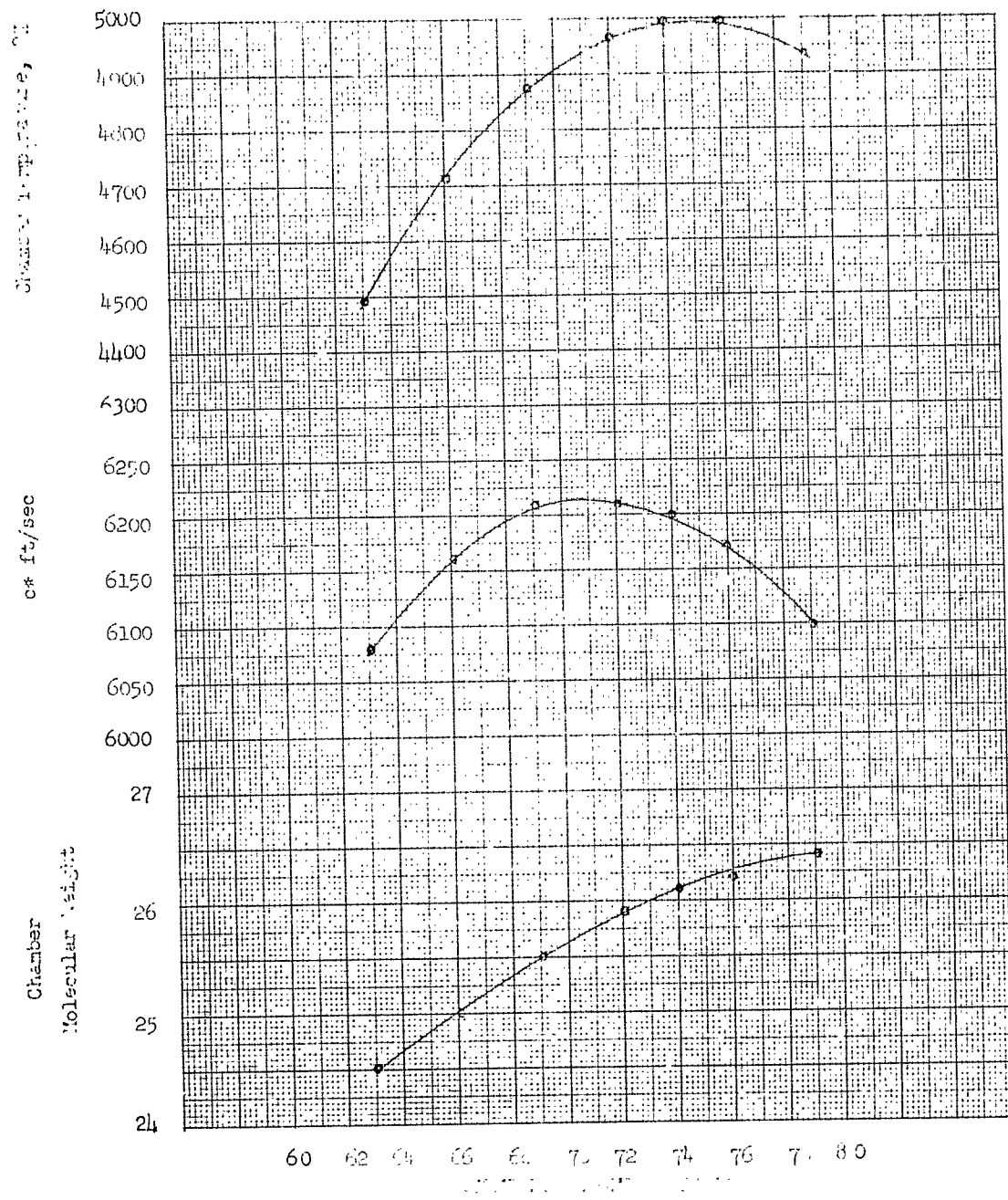




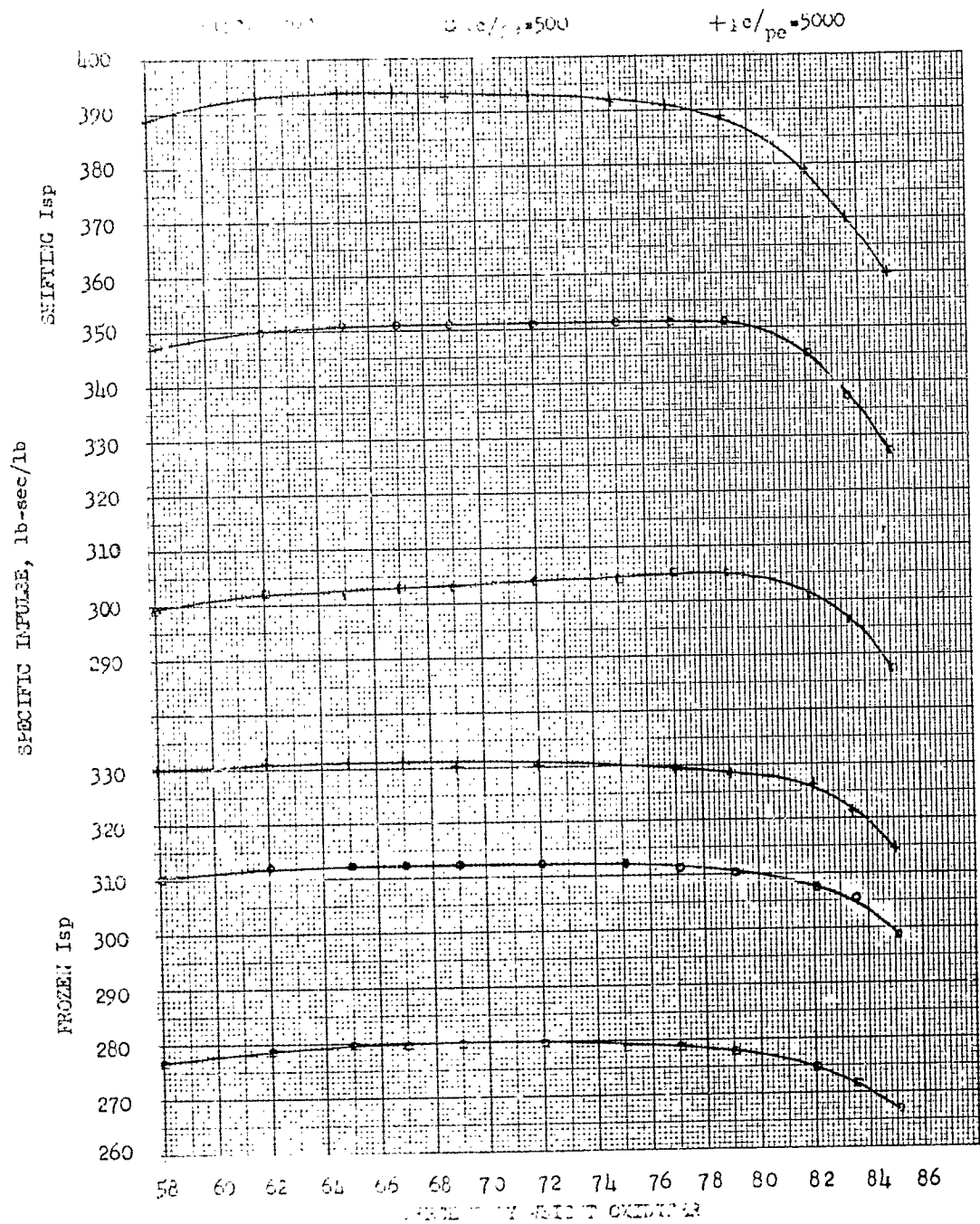




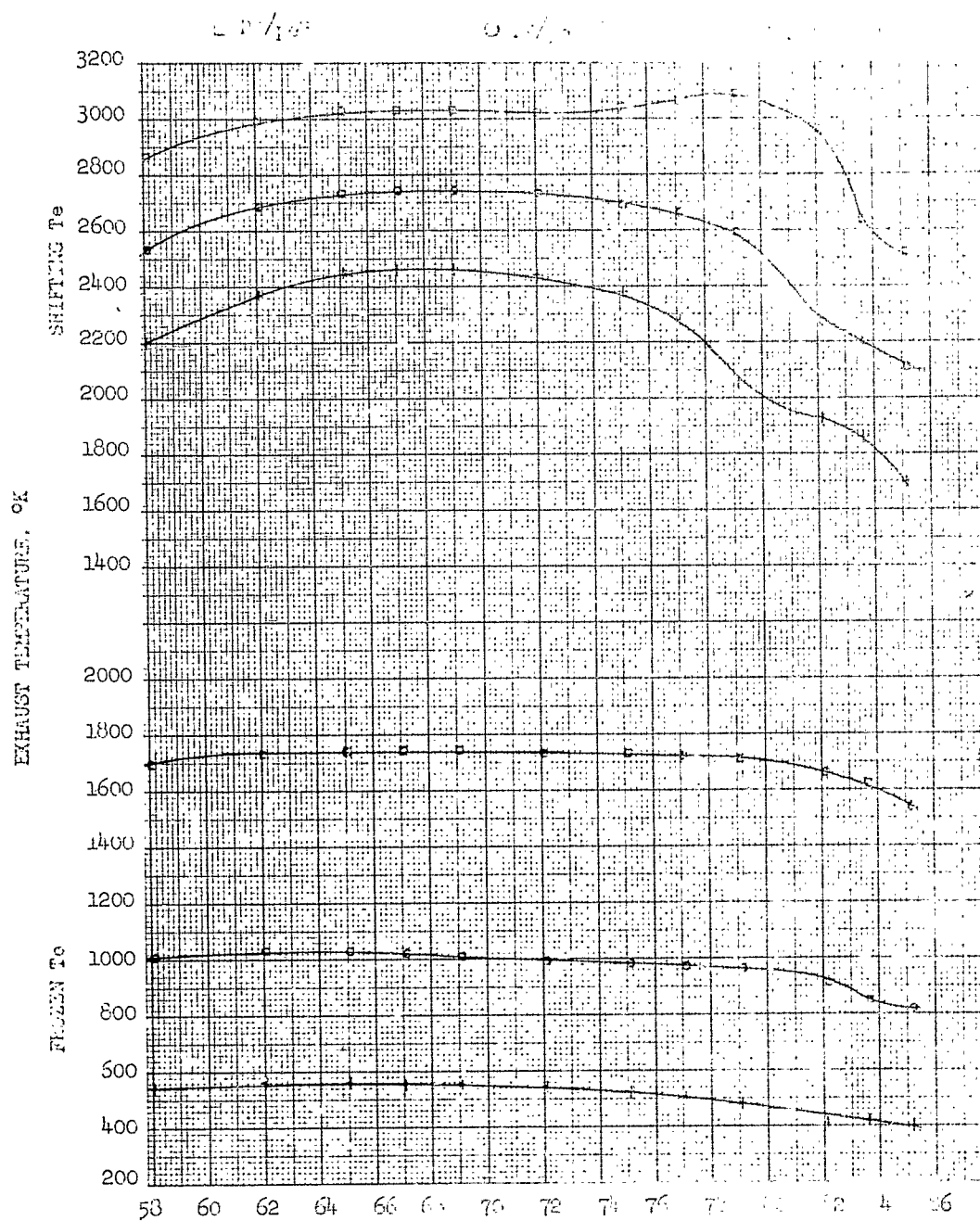
MAGNESIUM HYDRIDE - LIMITED FLUORINE PERFORMANCE CURVES FIGURE 276

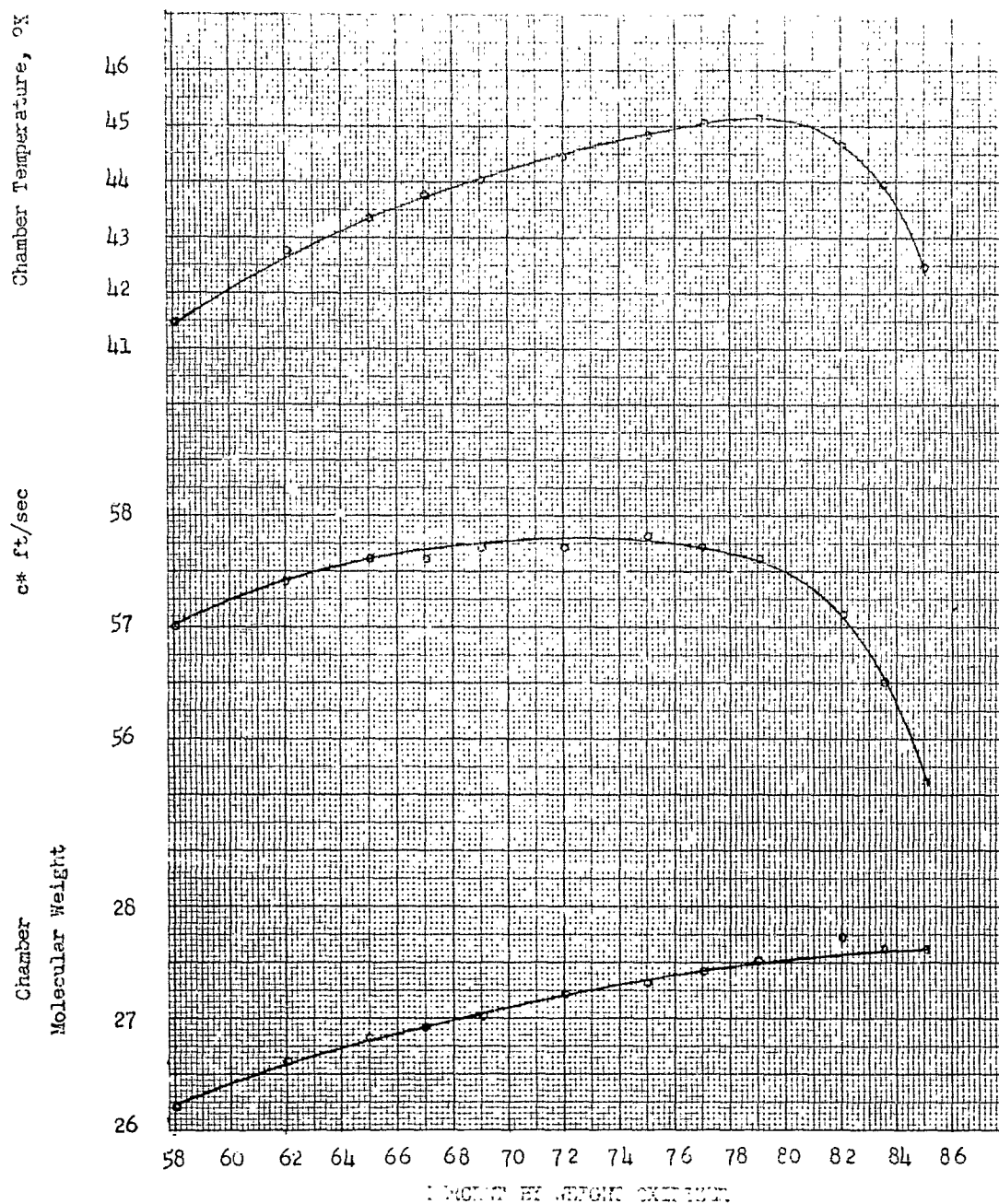


HYDROGEN PEROXIDE - OXYGEN DIFLUORIDE PERFORMANCE CURVES FIGURE 277
 at 1000 psi



MAGNESIUM NITRIDE - OXYGEN DIFLUORIDE PERFORMANCE





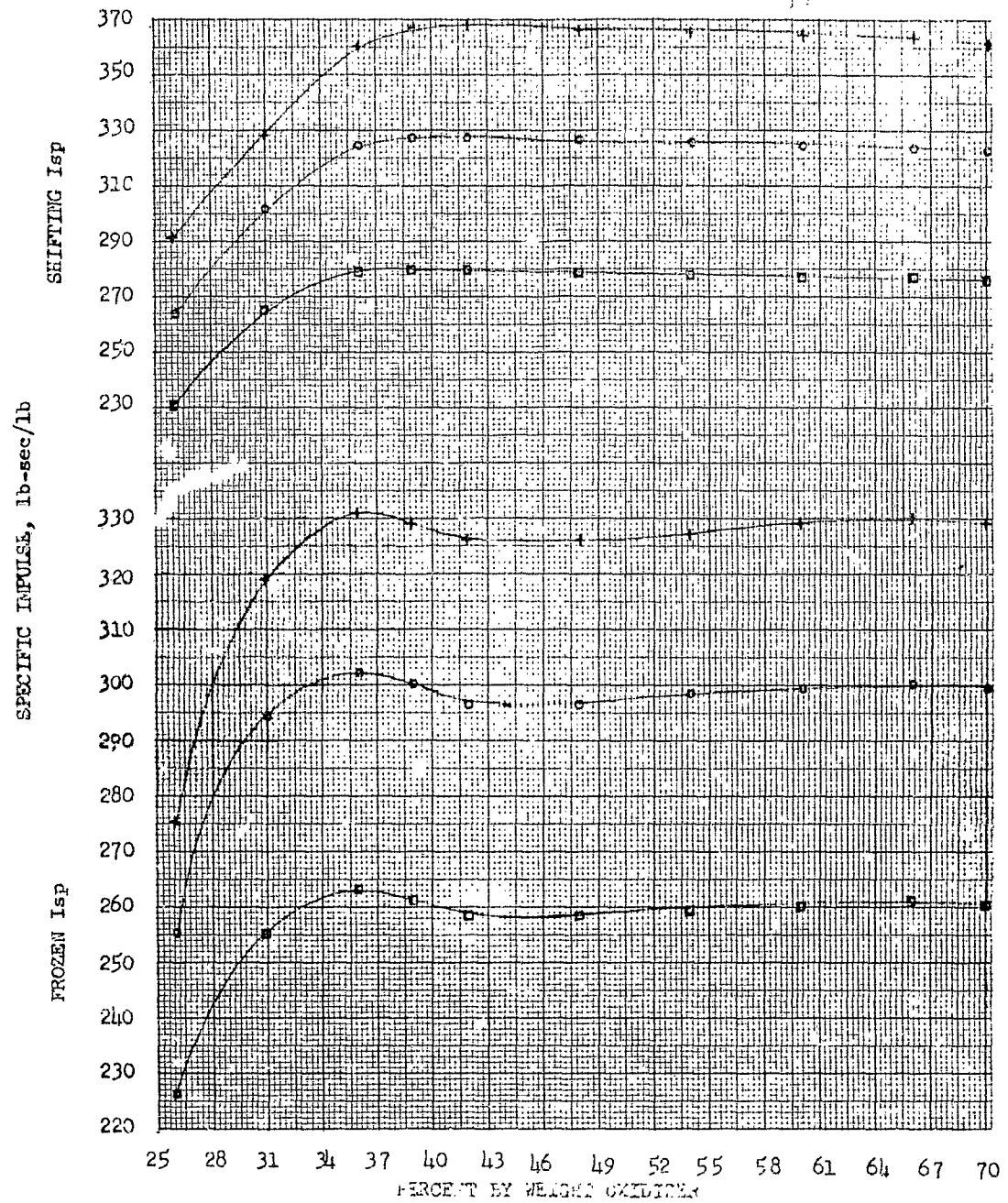
MAGNESIUM HYDRIDE - HYDROGEN PEROXIDE PERFORMANCE CURVES FIGURE 280

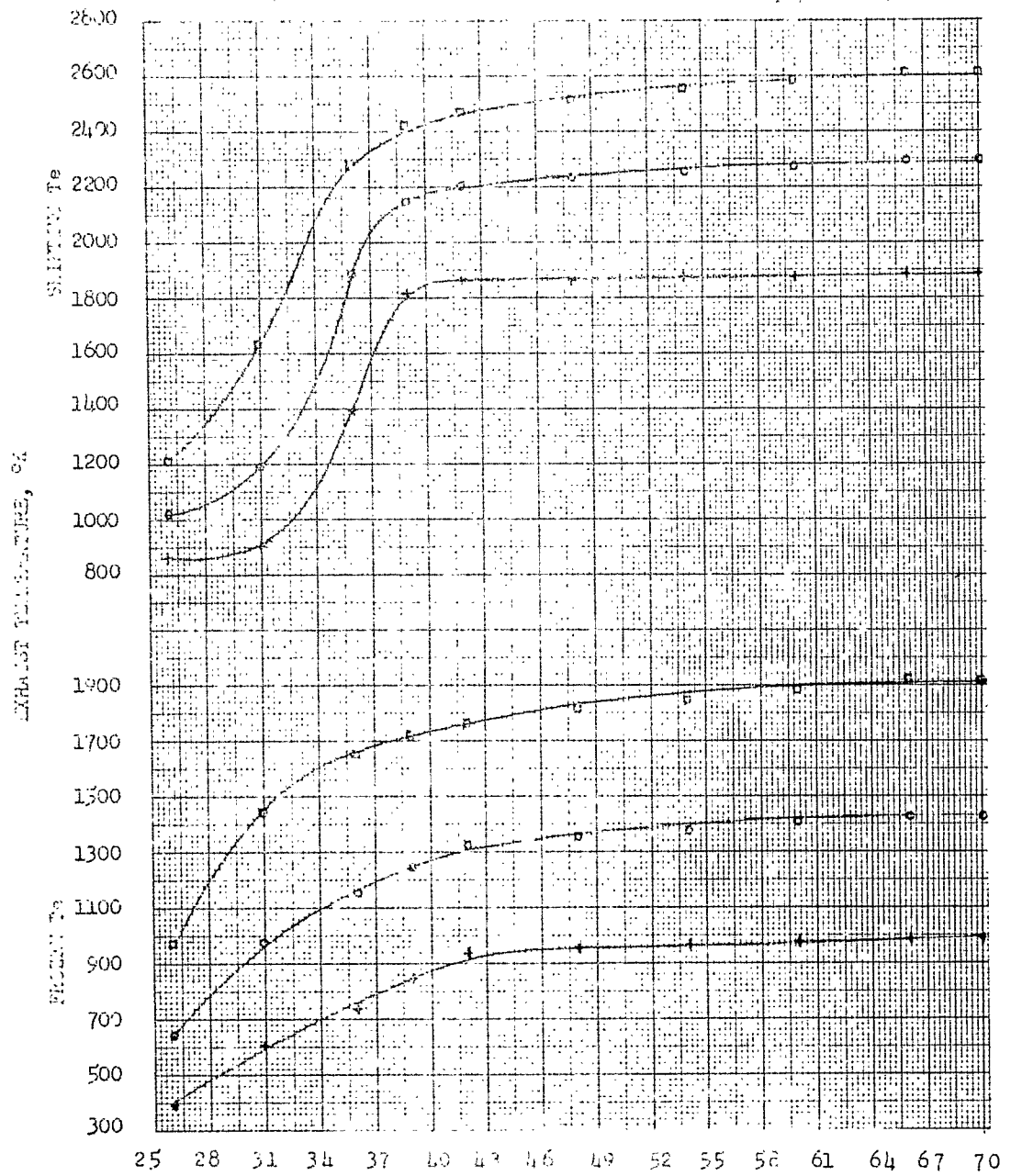
1/10 sec

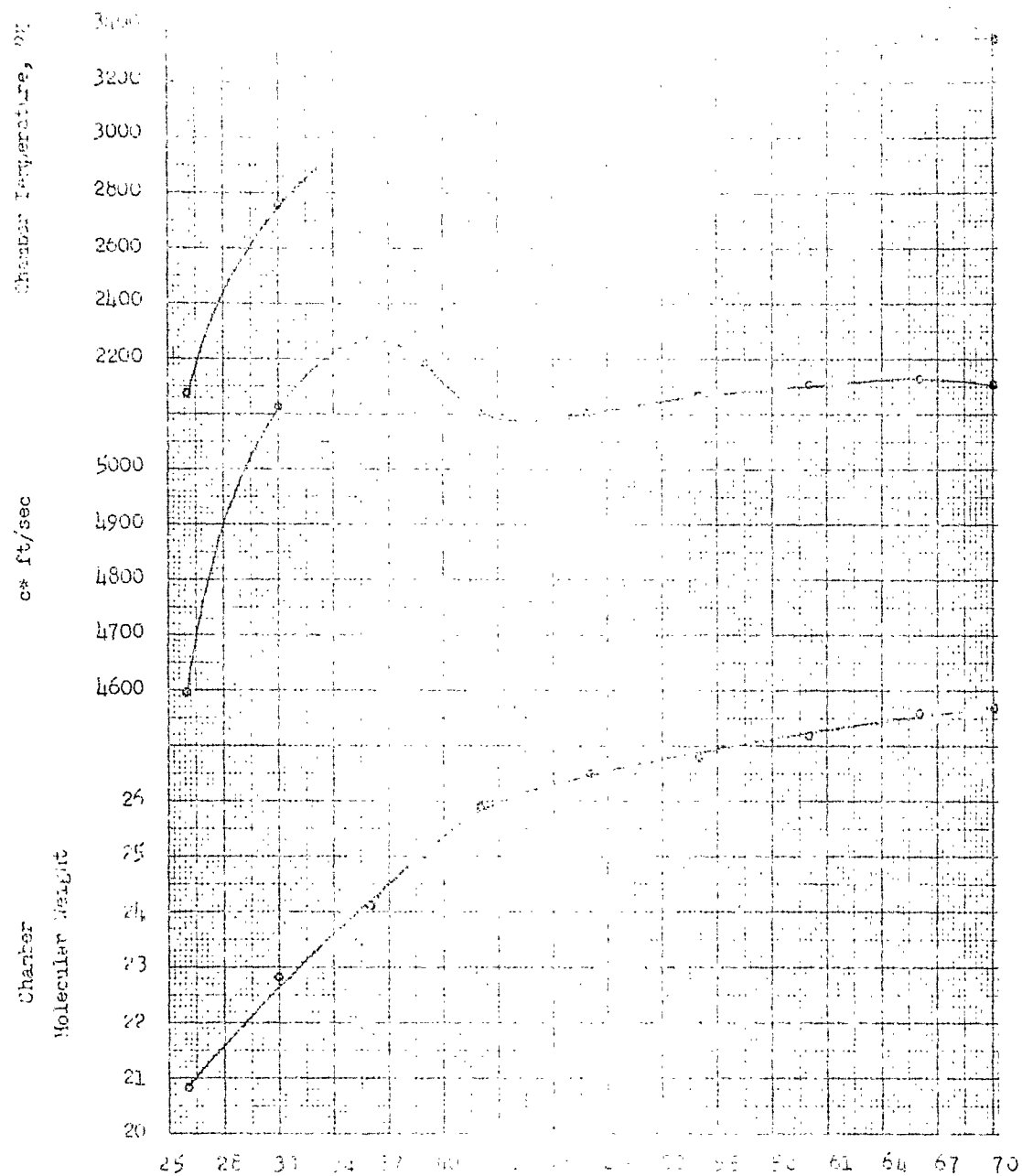
$\frac{1 \text{ lb}}{100 \text{ lb}} = 0.01$

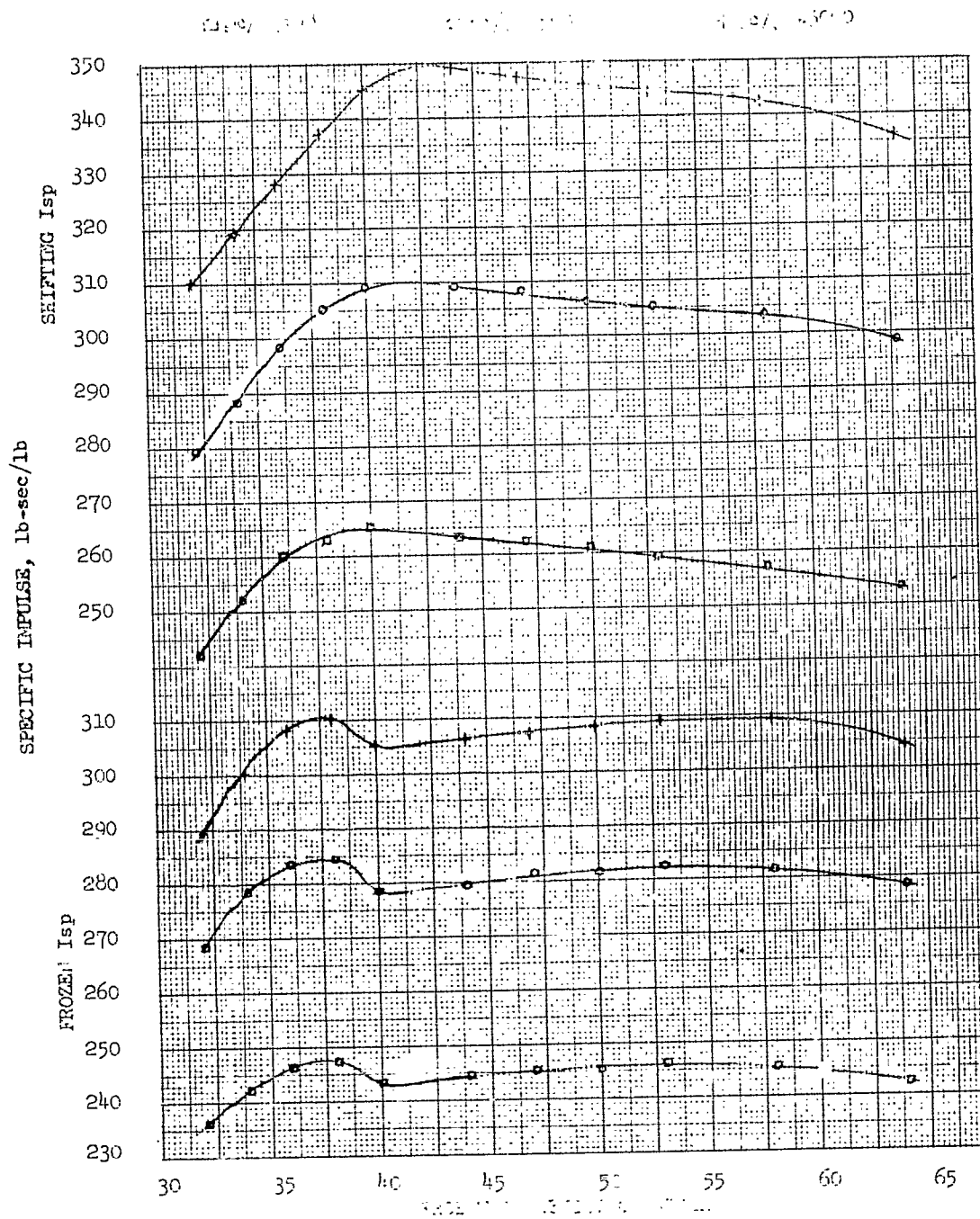
$\frac{1 \text{ lb}}{100 \text{ lb}} = 0.01$

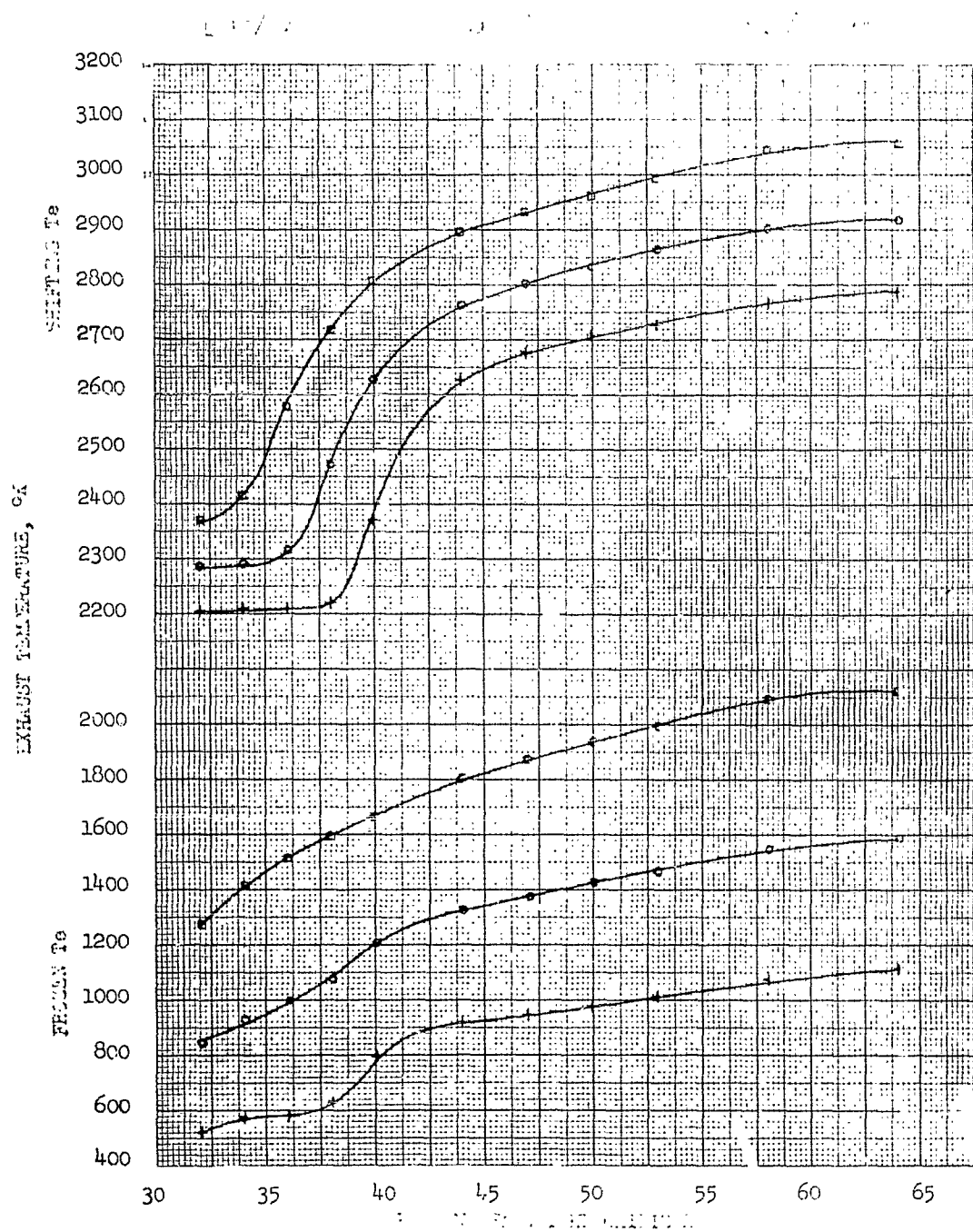
$\frac{1 \text{ lb}}{100 \text{ lb}} = 0.01$

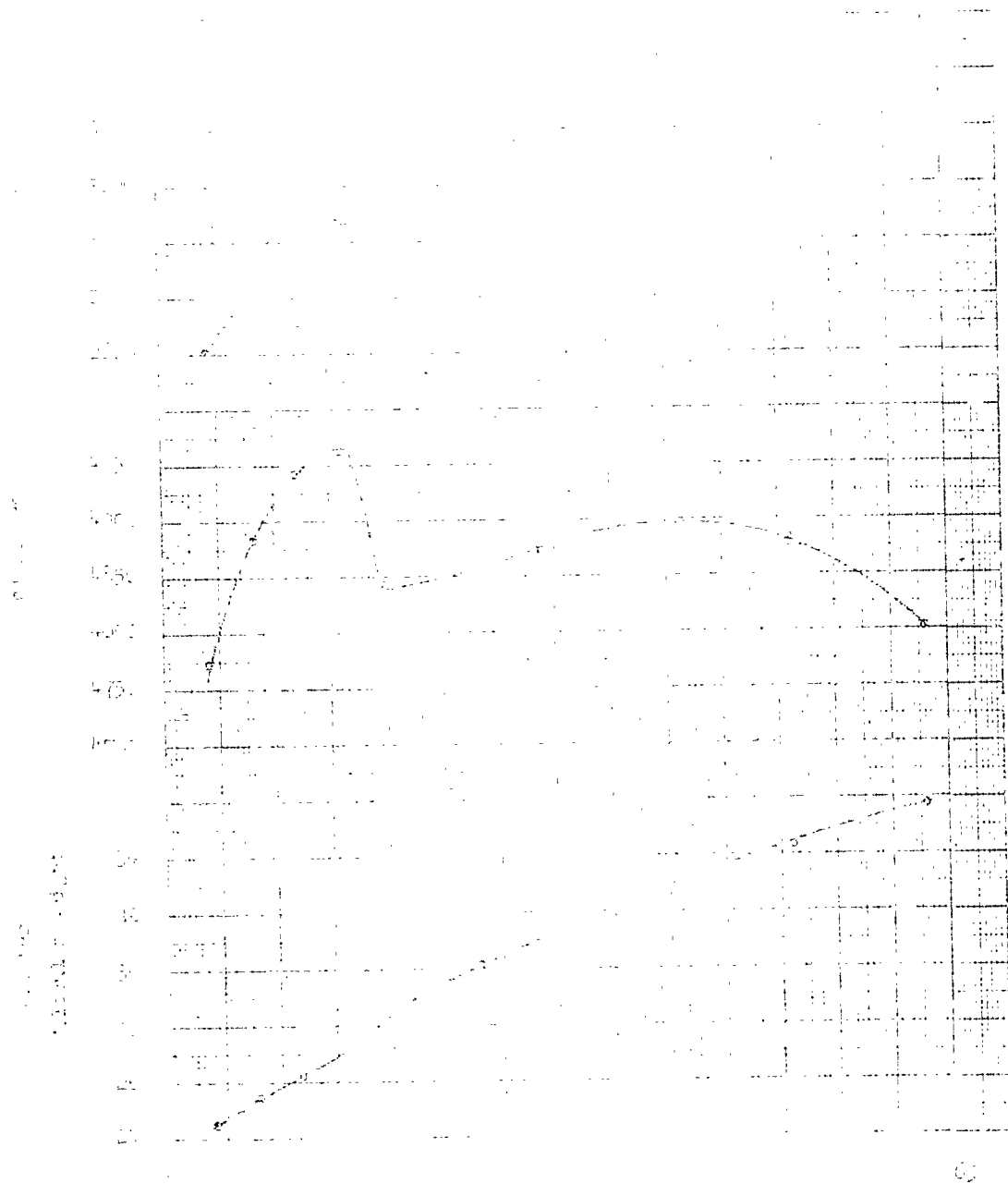


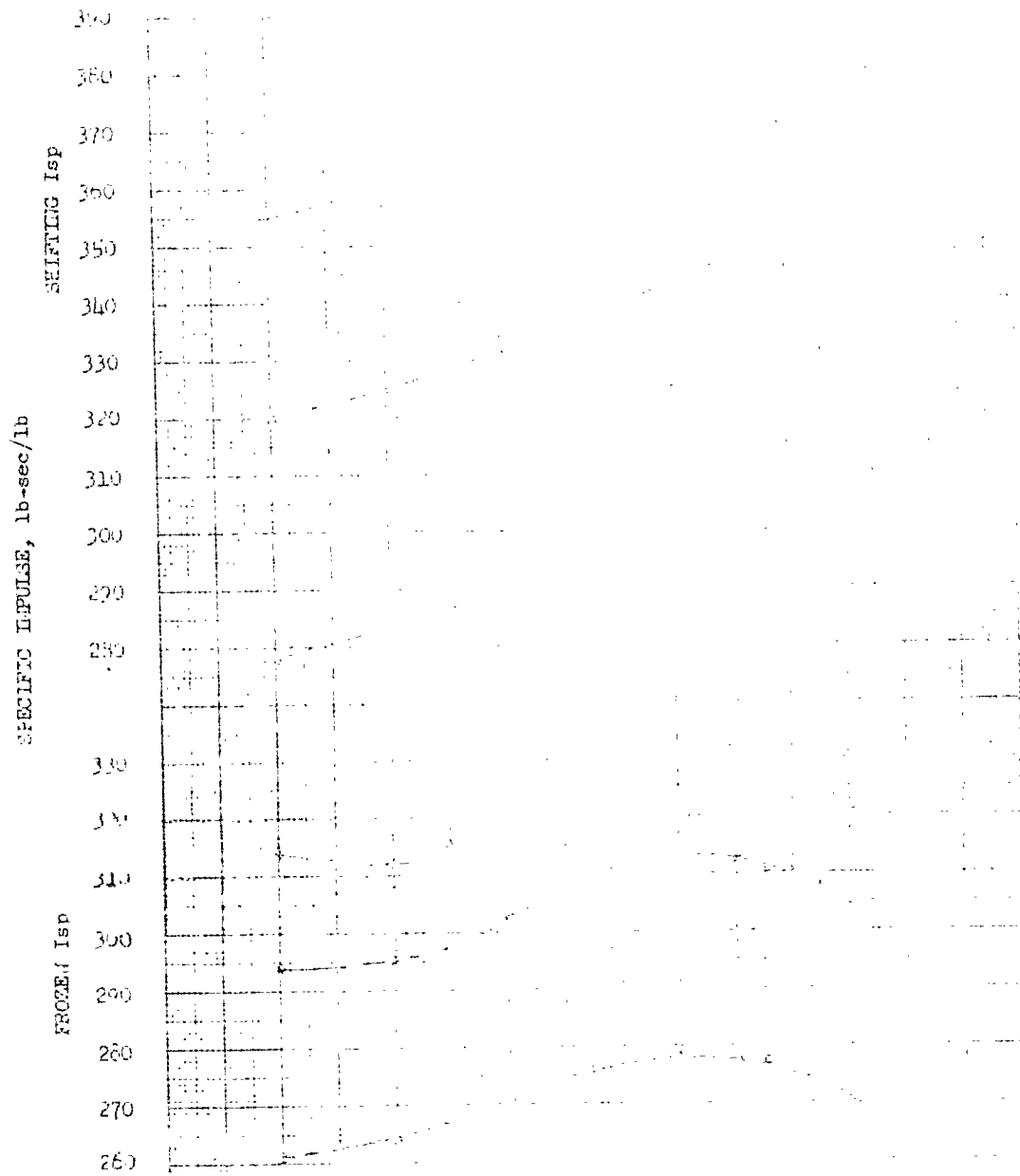


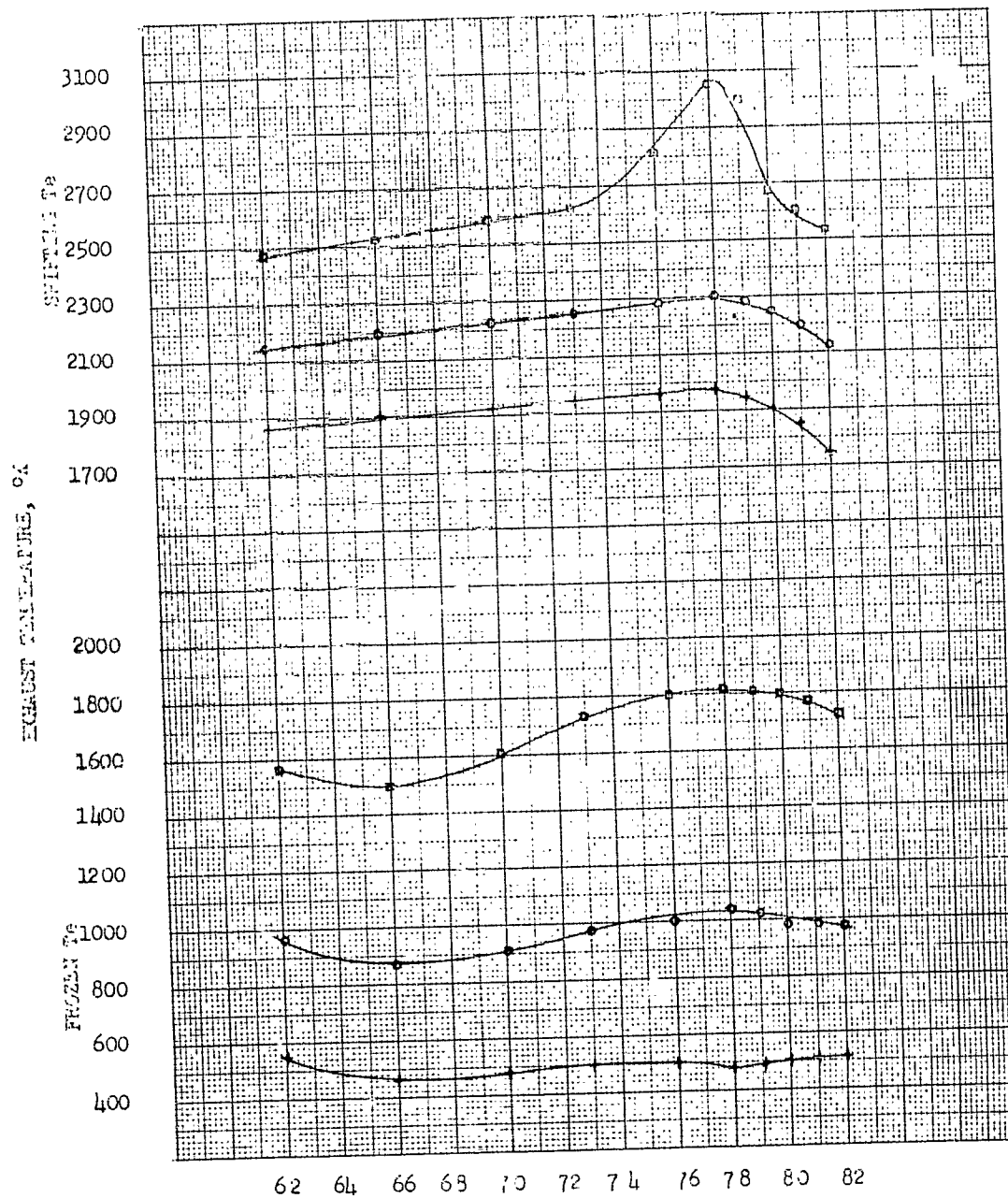




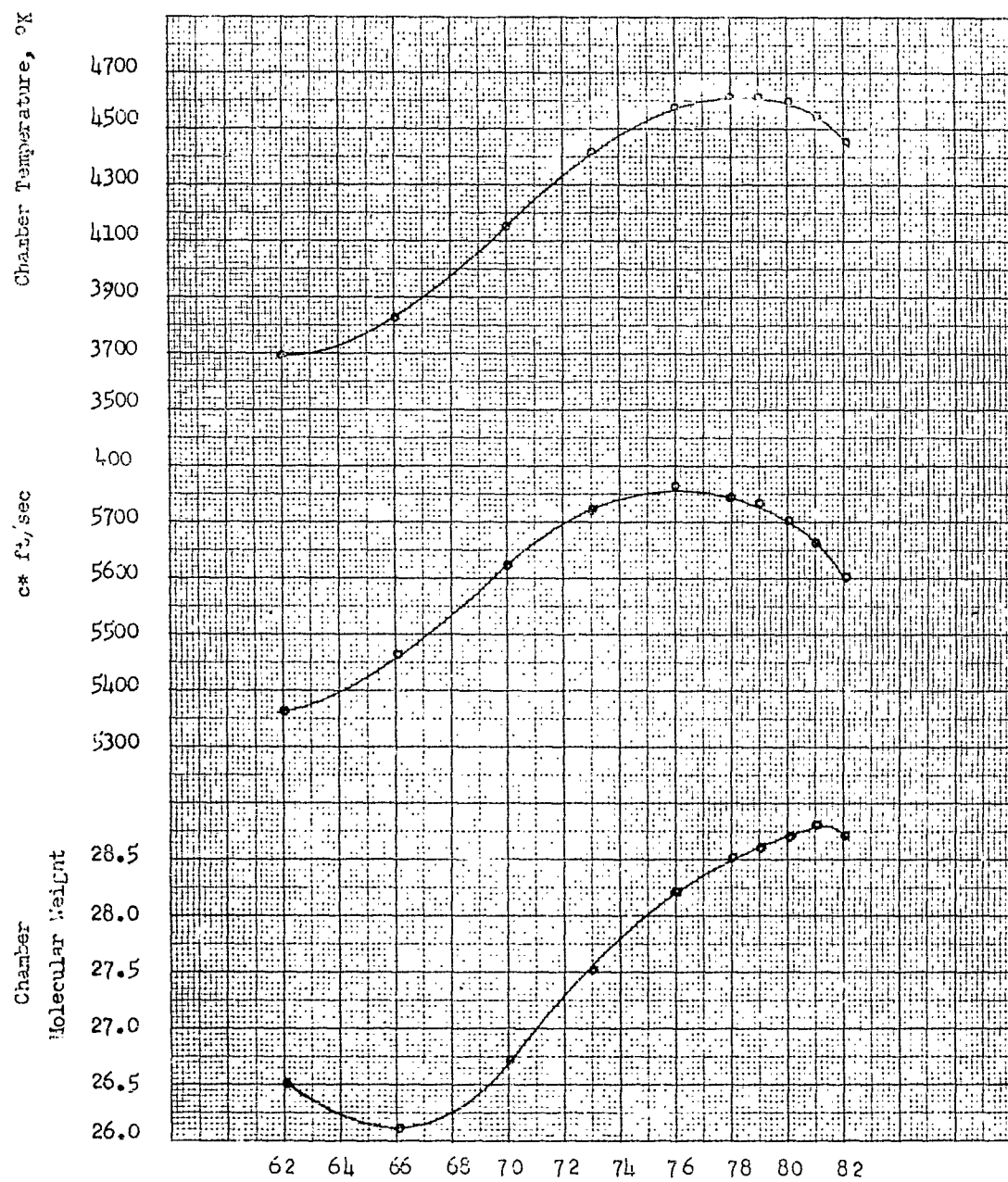


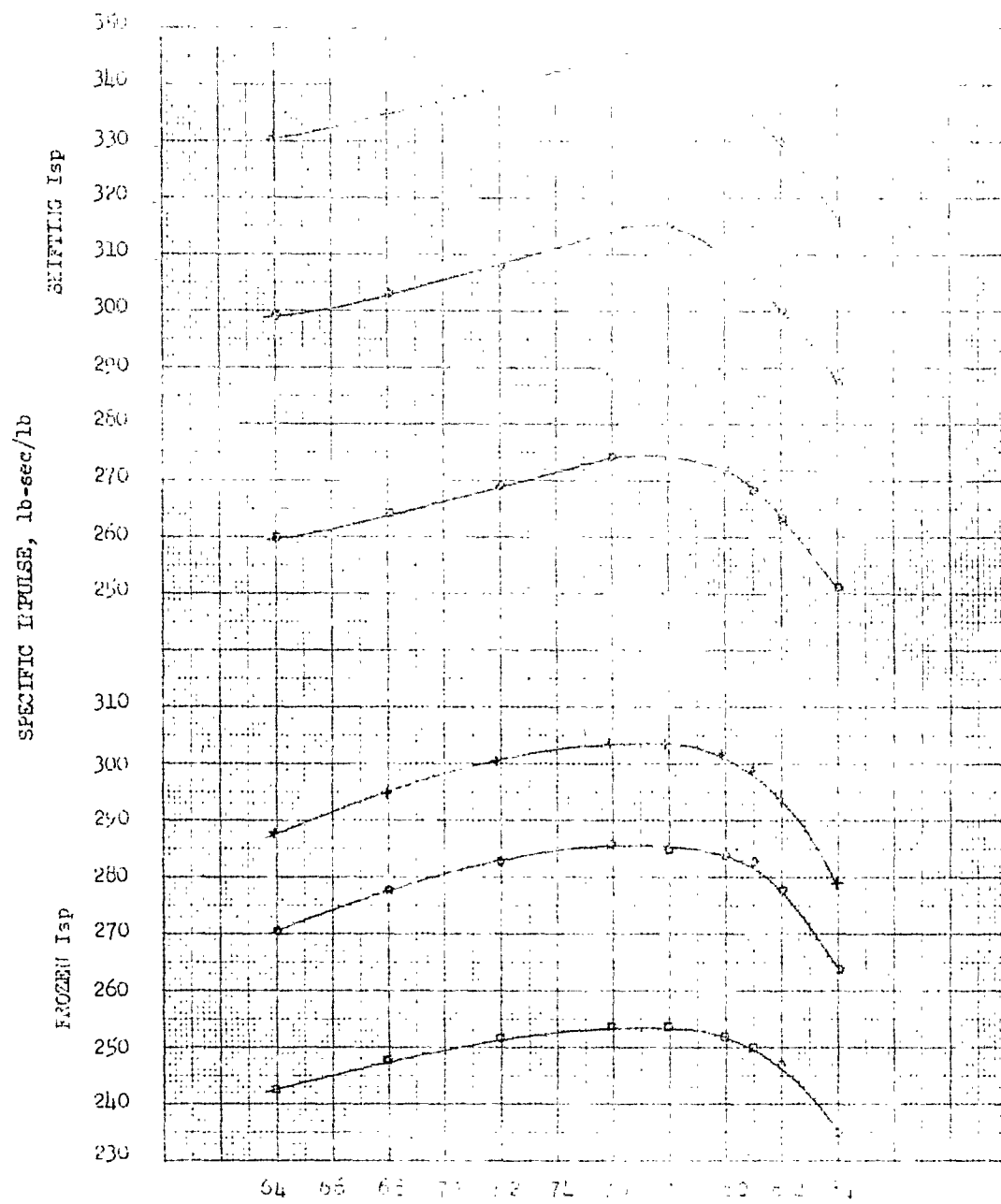






MAGNESIUM HYDRIDE - NITROGEN TRIFLUORIDE PERFORMANCE CURVES FIGURE 288





The figure consists of two vertically stacked line graphs sharing a common x-axis representing engine speed in RPM. The x-axis has major tick marks at 64, 66, 68, 70, 72, 74, 76, 78, 80, 82, and 84.

Top Graph: Shifted Tc (°C)

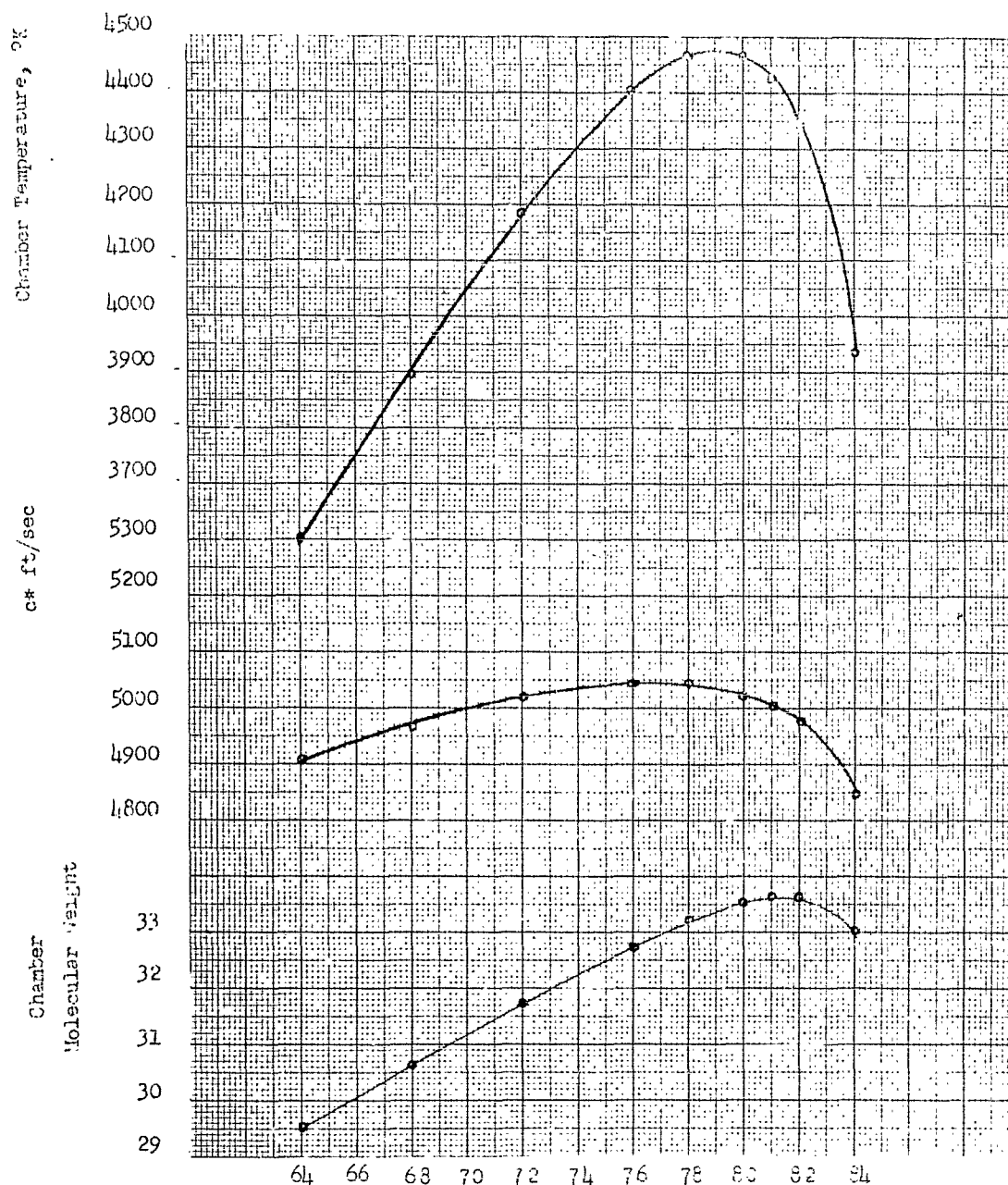
The y-axis for the top graph ranges from 1600 to 3000 in increments of 200. Four data series are plotted, labeled 1, 2, 3, and 4. Series 1 (open squares) starts at ~2380, peaks at ~2900 at 78 RPM, and ends at ~2380. Series 2 (open circles) starts at ~2050, peaks at ~2320 at 78 RPM, and ends at ~2000. Series 3 (solid circles) starts at ~1780, peaks at ~1820 at 78 RPM, and ends at ~1650. Series 4 (open triangles) starts at ~1780, peaks at ~1820 at 78 RPM, and ends at ~1650.

Bottom Graph: Exhaust Temperature (°C)

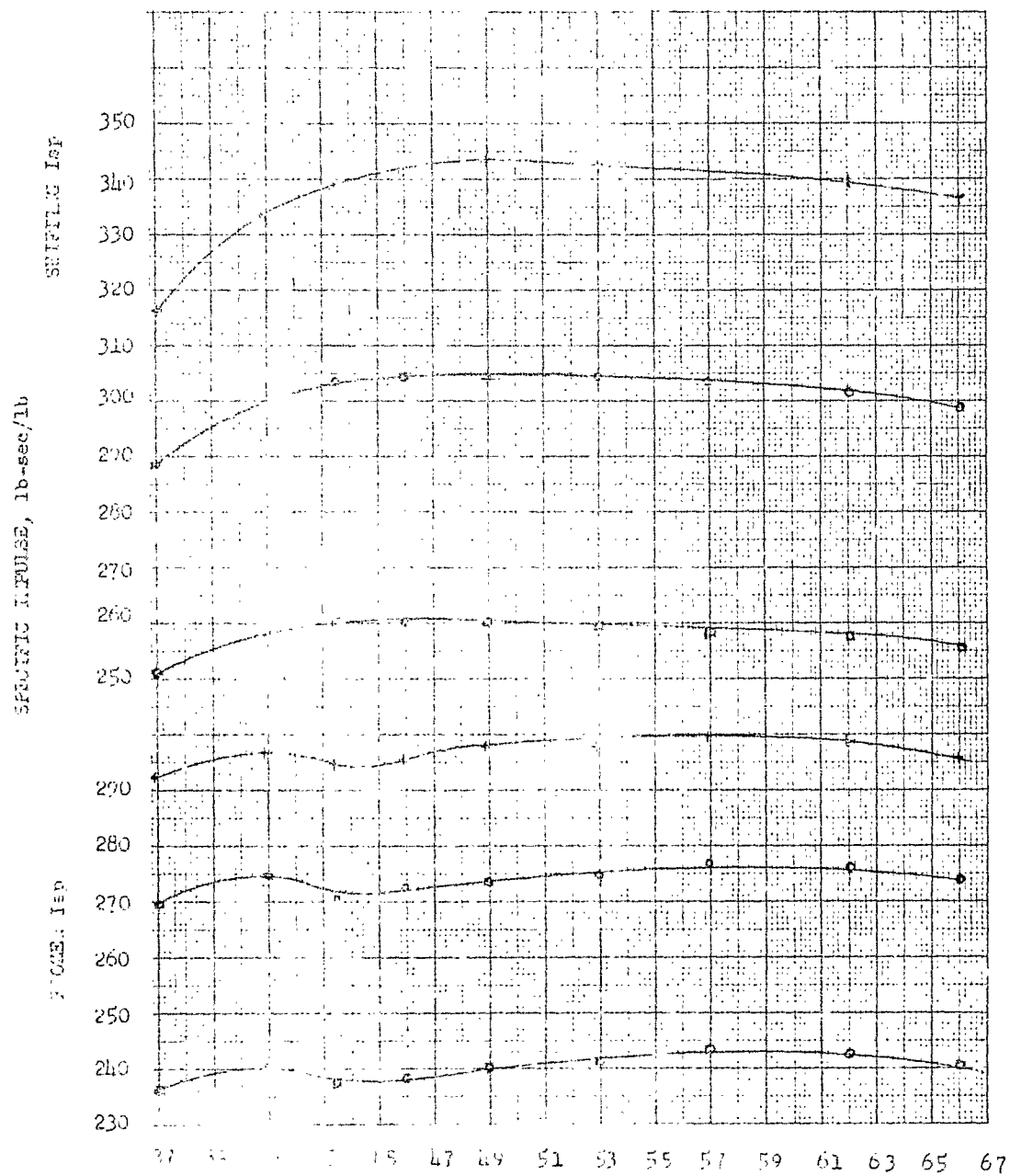
The y-axis for the bottom graph ranges from 400 to 1800 in increments of 200. Four data series are plotted, labeled 1, 2, 3, and 4. Series 1 (open squares) starts at ~1380, peaks at ~1720 at 78 RPM, and ends at ~1400. Series 2 (open circles) starts at ~830, peaks at ~1000 at 78 RPM, and ends at ~780. Series 3 (solid circles) starts at ~430, peaks at ~480 at 82 RPM, and ends at ~400. Series 4 (open triangles) starts at ~430, peaks at ~480 at 82 RPM, and ends at ~400.

17

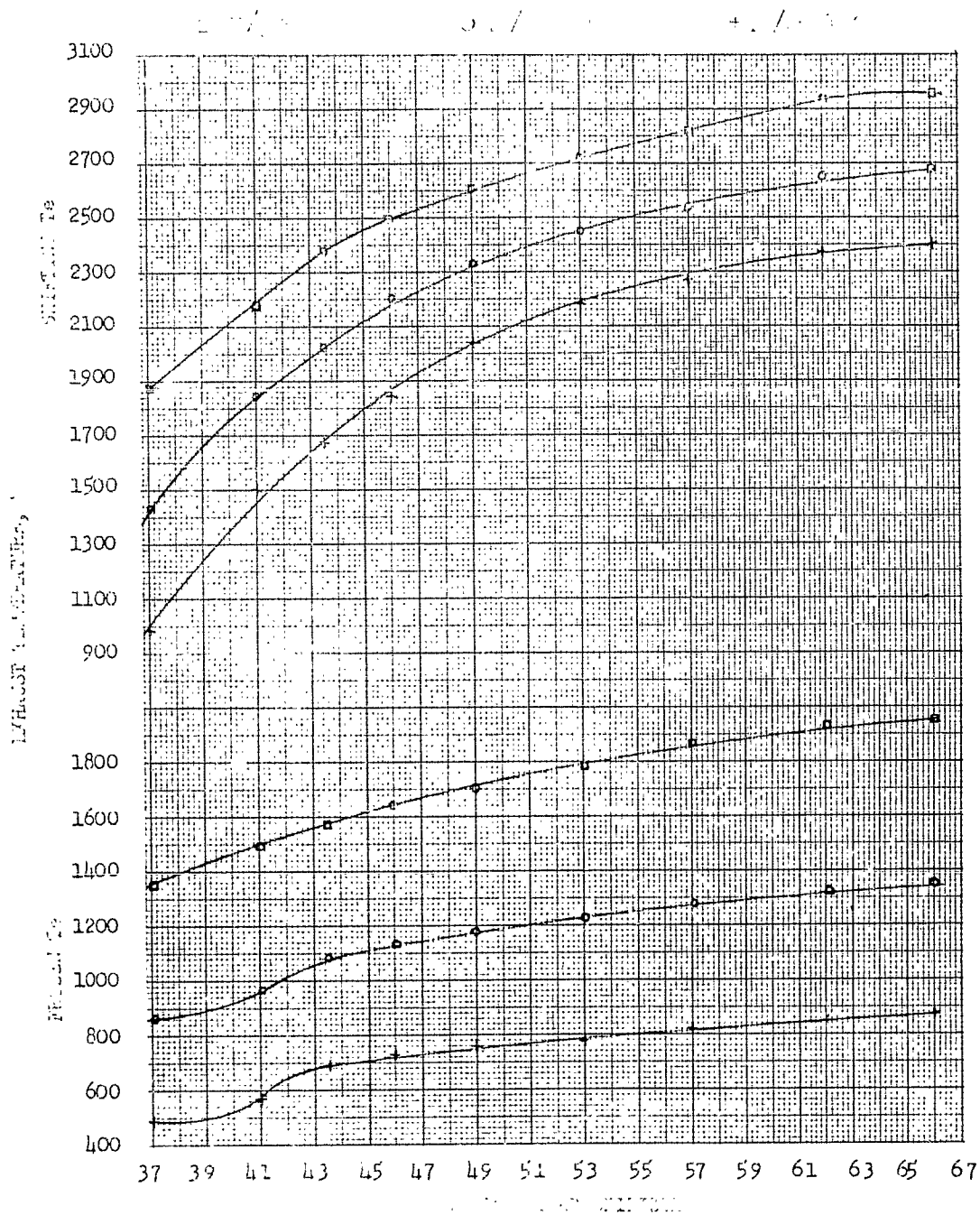
MAGNESIUM HYDRIDE - CHLORINE TRIFLUORIDE PERFORMANCE CURVES FIGURE 291

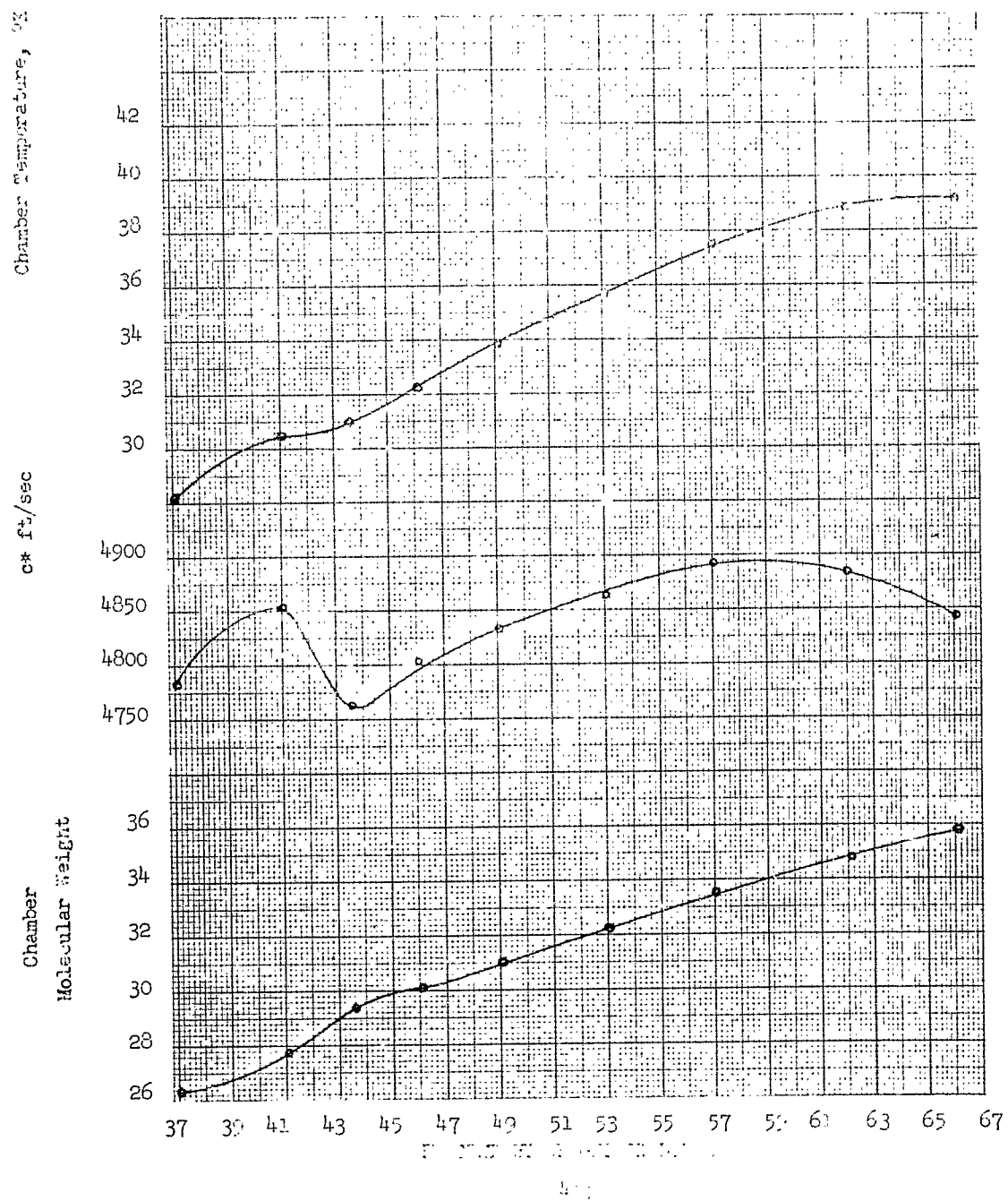


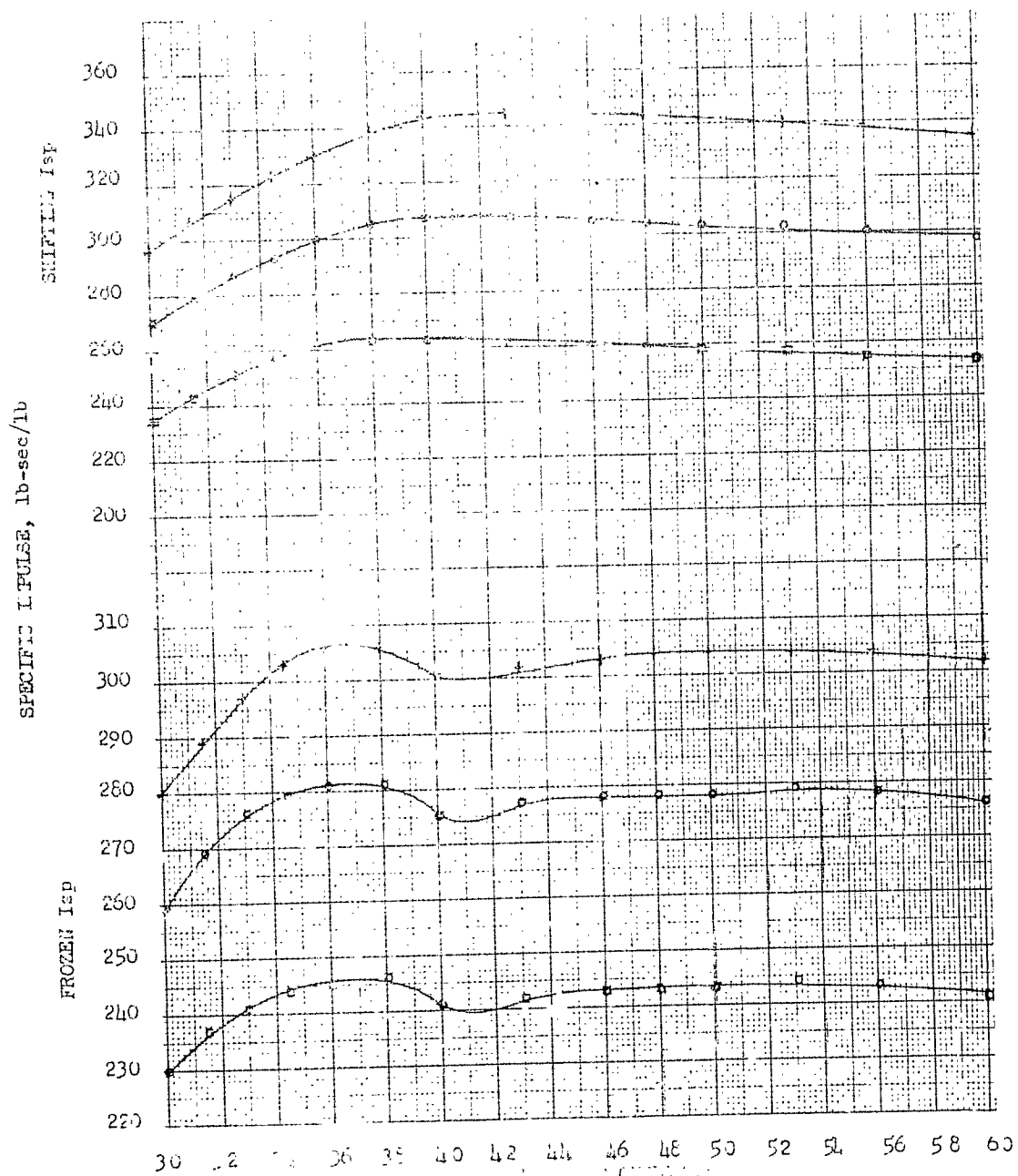
MEASUREMENT OF THE EFFECT OF REACTION RATE ON THE CURVES FIGURE 202

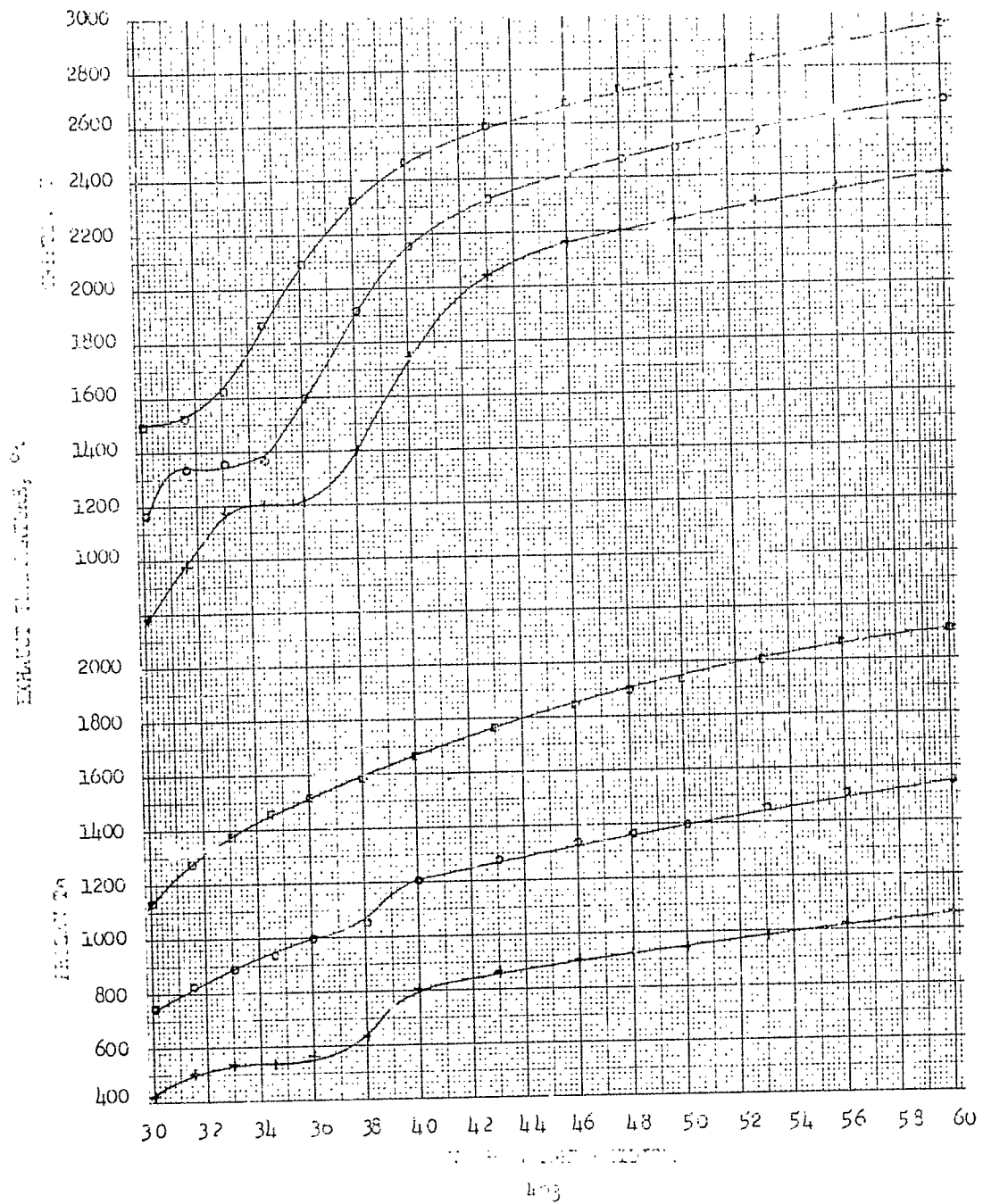


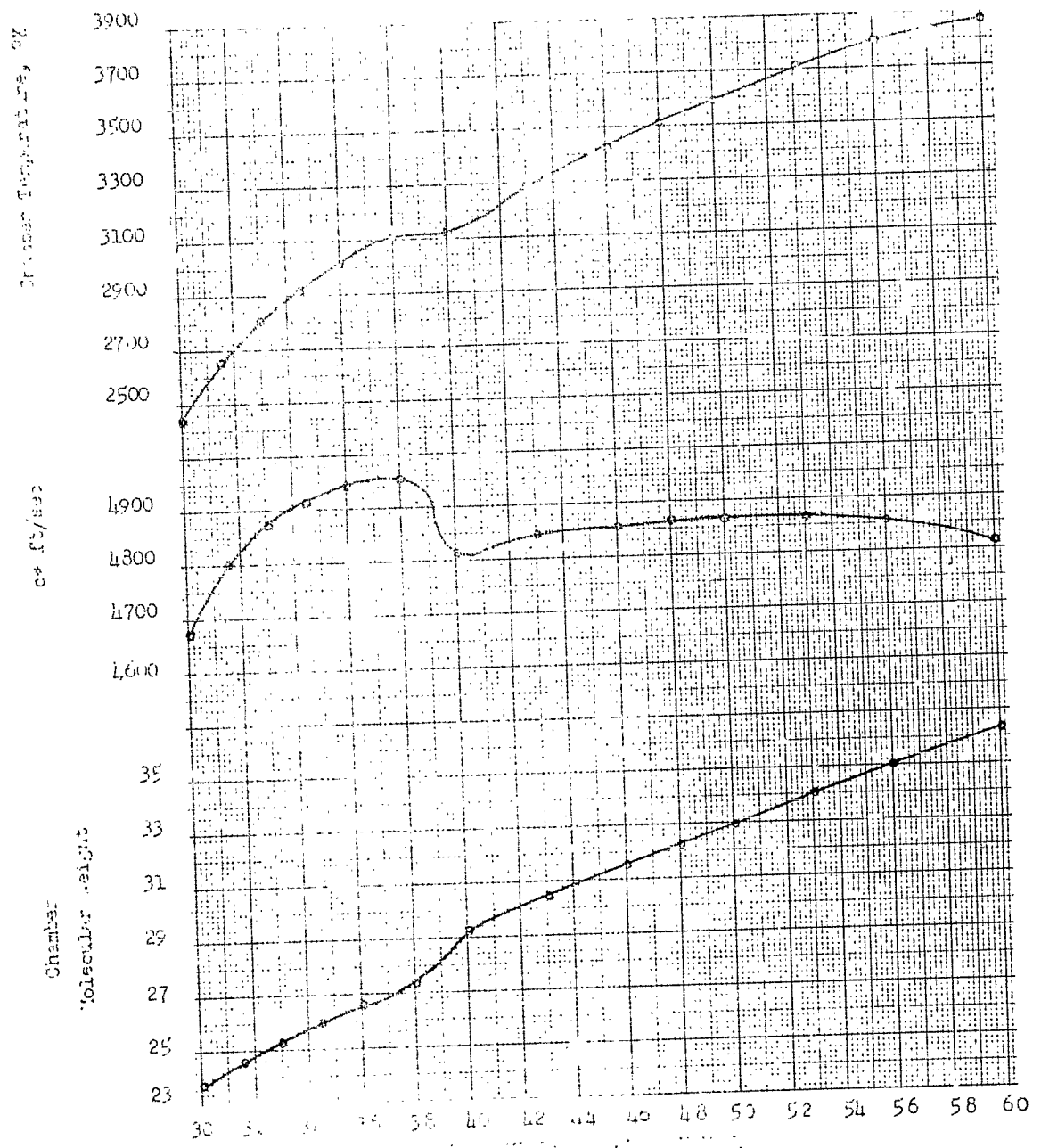
REGRESSION EQUATIONS - PERCHLORYL FLUORIDE PERFORMANCE CURVES FIGURE 293



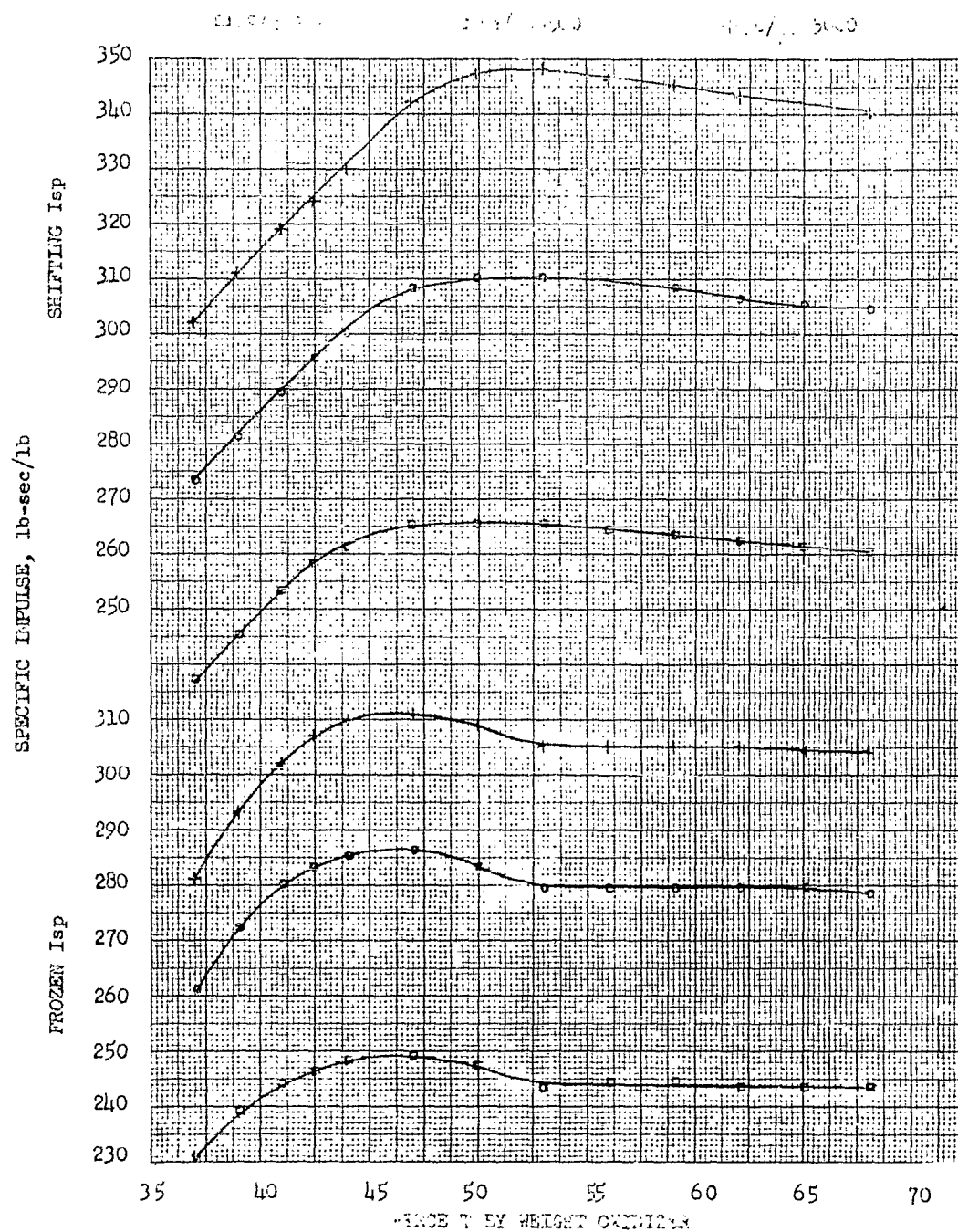




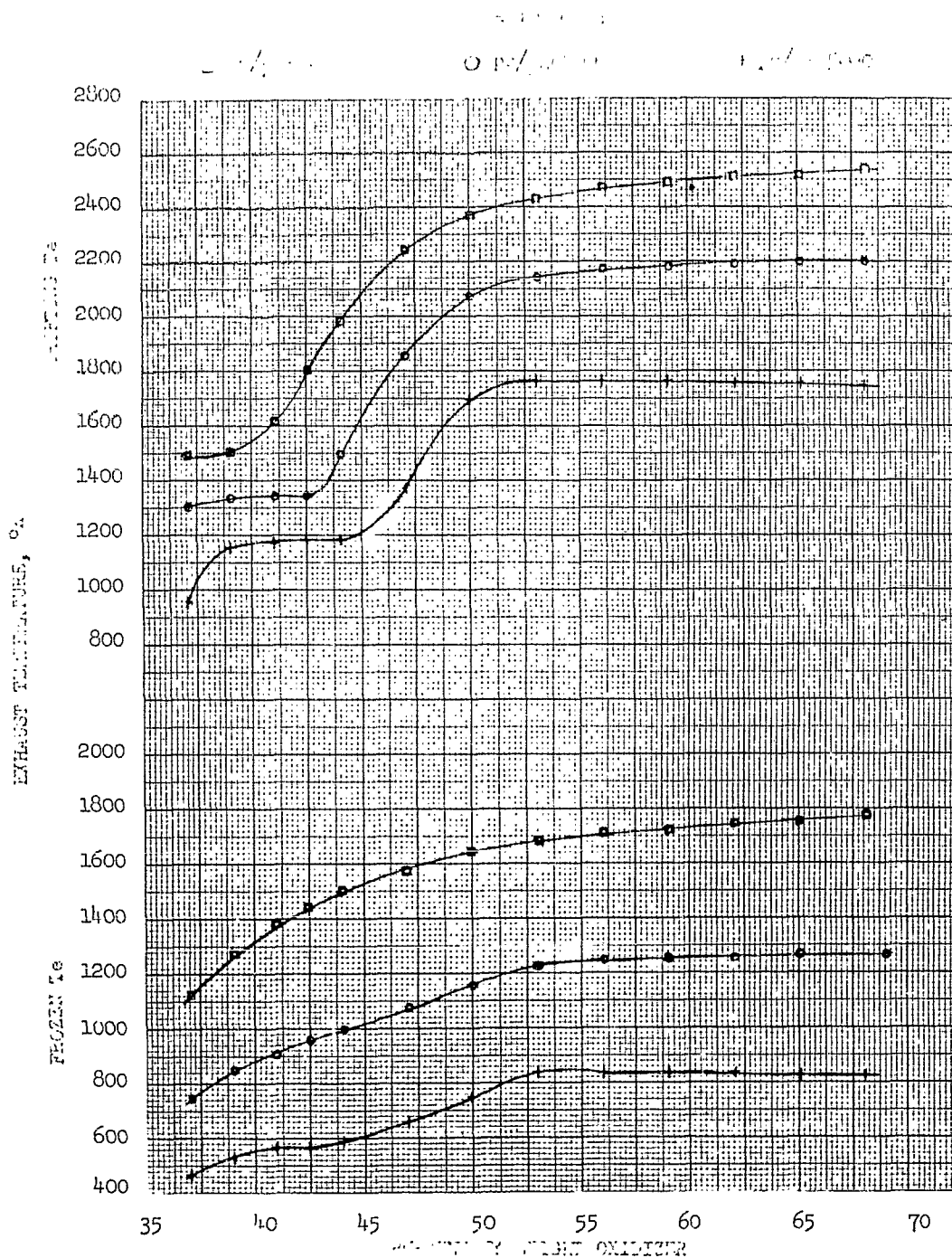


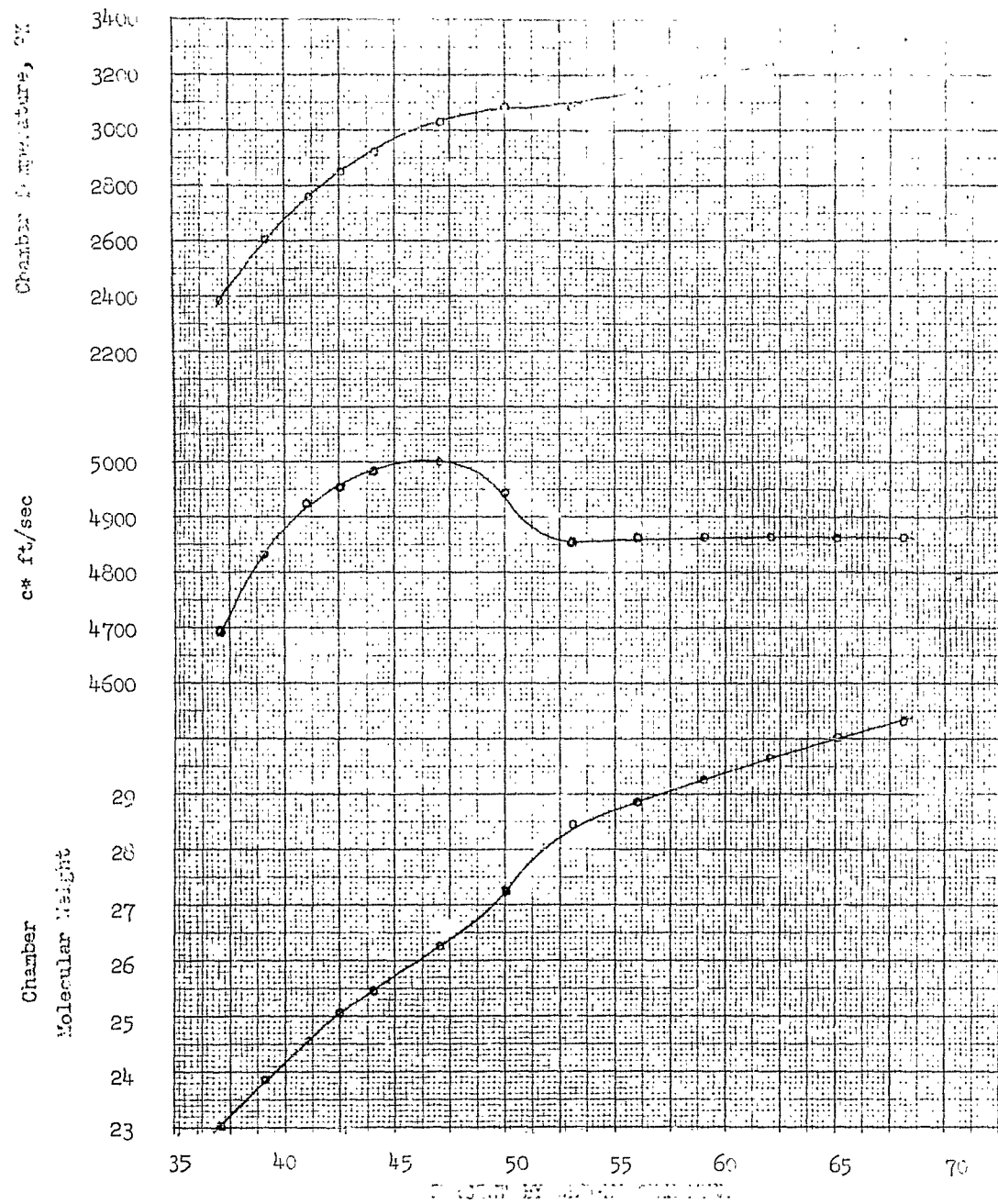


MAGNESIUM NITRIDE - AMMONIUM PERCHLORATE PERFORMANCE CURVES FIGURE 298



MAGNESIUM BURNING - ALUMINUM LEADERSHIP PERFORMANCE CURVES FIGURE 2.11





APPENDIX D

Tables of Complete Thermodynamic Data
and Rocket Performance Parameters
for Selected Propellant Compositions

TABLE 1

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	REF. TEMP.
	O2	76.000		90.200
	H2	24.000		20.400
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	
	O2	-3.0800	1.142	
	H2	-1.8870	710.0E-4	
ATOMIC COMPOSITION (GM AT/100GM)				
	H	23.8095		
	O	4.7500		
PROPELLANT ENTHALPY		KCAL/100 GM		
	-29.779			
PROPELLANT DENSITY		GM/CC		
	0.2472			
CHAMBER		EXHAUST		
	1000.0	14.70		
PRESSURE (PSI)				
SHIFTING EQUILIBRIA				
ISP (SEC)		389.05	431.02	456.95
IVSP (LB-SEC/CU IN)		3.4743	3.8492	4.0807
TEMPERATURE (K)	2570.4	1059.1	646.04	352.76
CP (CAL/GM-DEG.K)	1.2154	0.99846	0.92090	0.88221
MOL. WT.-EFFECTIVE	8.3846	8.4000	8.4000	8.4000
CP/CV -EFFECTIVE	1.2422	1.5105	1.5457	1.5664
CF -APPROX.		1.5691	1.7384	1.8430
PEAF/M (SEC)		28.019	15.427	7.9456
AE/AT -APPROX.		7.6896	31.109	160.23
FROZEN EQUILIBRIA				
ISP (SEC)		387.75	430.14	454.98
TEMPERATURE (K)	2570.4	1046.5	629.56	349.26
C* (FT/SEC)	7977.4			
CF (SEC)		1.5638	1.7348	1.8350
PEAF/M (SEC)		27.829	15.092	7.9155
AE/AT		7.6373	30.434	159.62

TABLE 2

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	2570.4	1059.1	646.04	352.76
ENTROPY (CALORIES/DEG.K)	-29.779	-203.73	-243.29	-269.75
HEAT CAPACITY (CAL/K)	569.88	569.88	569.88	569.88
MOLES OF GAS	121.54	99.846	92.090	88.221
MOLECULAR COMPOSITION:	11.927	11.905	11.905	11.905
H	0.0379	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
H2	7.1387	7.1548	7.1548	7.1548
H2O	4.7442	4.7500	4.7500	4.7500
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0058	0.0000	0.0000	0.0000

501

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	FORMULA	HEAT OF FORM.	DENSITY	REF.	TEMP.
	F2	92.000			-3.4670	1.510		85.200
	H2	8.0000			-1.8870	710.0E-4		20.400
	INGREDIENT DATA:							
	F2							
	H2							
	ATOMIC COMPOSITION(GM AT/100GM)							
	H	7.9365						
	F	4.6421						
	PROPELLANT ENTHALPY	-15.892	KCAL/100 GM					
	PROPELLANT DENSITY	0.5760	GM/CC					
	CHAMBER		EXHAUST					
	1000.0		14.70					
	PRESSURE (PSI)							
	SHIFTING EQUILIBRIA							
	ISP (SEC)		407.22			456.56		486.86
	IVSP(LB-SEC/CU IN)		8.4751			9.5019		10.132
	TEMPERATURE (K)	4462.0	2395.6			1500.7		803.36
	CP (CAL/GM-DEG.K)	0.59665	0.53915			0.44985		0.45101
	MOL. WT.-EFFECTIVE	14.240	15.592			15.651		15.651
	CP/CV -EFFECTIVE	1.3053	1.3096			1.3499		1.3918
	CF -APPROX.		1.6533			1.6536		1.9766
	PEAE/M (SEC)		32.621			18.158		9.1151
	AE/AT -APPROX.		9.0118			36.859		185.03
	FROZEN EQUILIBRIA							
	ISP (SEC)		377.72			420.67		441.17
	TEMPERATURE (K)	4462.0	1540.8			734.49		298.16
	C* (FT/SEC)	7924.8						
	CF		1.5335			1.7079		1.7911
	PEAE/M (SEC)		24.766			10.600		4.1032
	AE/AT		6.8418			21.518		83.293

TABLE 4

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4462.0	2395.6	1500.7	803.36
TEMPERATURE (KELVIN)	-15.882	-206.46	-255.45	-288.30
ENTHALPY (KILOCALORIES)	355.17	355.17	355.17	355.17
ENTROPY (CALORIES/DEG.K)	59.665	53.915	48.985	45.101
HEAT CAPACITY (CAL/K)	7.0223	6.4137	6.5894	6.3893
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	1.0934	0.0466	0.0002	0.0000
F	0.1726	0.0002	0.0000	0.0000
H2	1.0866	1.5230	1.5471	1.5472
HF	4.6695	4.8419	4.8421	4.8421
F2	0.0000	0.0000	0.0000	0.0000

TABLE 5

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	OF2	85.500		1.530	128.00
	H2	14.500		710.0E-4	20.400
INGREDIENT DATA:					
	OF2		HEAT OF FORM.		
	H2		3.6000		
			-1.8870		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	14.3849			
	O	1.5833			
	F	3.1667			
PROPELLANT ENTHALPY					
		-7.8722	KCAL/100 GM		
PROPELLANT DENSITY					
		0.3844	GM/CC		
PRESSURE (PSI)					
		1000.0	EXHAUST	0.0139	LB/CU IN
SHIFTING EQUILIBRIA					
	ISP (SEC)			EXHAUST	0.2000
	IVSP(LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)	3590.6		457.02	485.43
	MOL. WT.-EFFECTIVE	0.86195		6.3482	6.7428
	CP/CV -EFFECTIVE	10.995		1022.2	553.04
	CF -APPROX.	1.2653		0.67995	0.63908
	PEAF/M (SEC)			11.395	11.395
	AE/AT -APPROX.			1.3450	1.3753
FROZEN EQUILIBRIA					
	ISP (SEC)			1.7976	1.9094
	TEMPERATURE (K)			16.971	8.6441
	C# (FT/SEC)			33.376	170.00
	CF (SEC)				
	PEAF/M (SEC)				
	AE/AT				
		394.25		441.95	466.94
		1377.8		722.17	318.96
		1.5507		1.7384	1.8367
		27.479		12.849	5.3712
		7.3548		25.270	105.64

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	3590.6	1663.2	1022.2	553.04
ENTROPY (CALORIES/DEG.K)	-7.8722	-201.58	-247.92	-278.69
HEAT CAPACITY (CAL/K)	460.58	460.58	460.58	460.58
MOLES OF GAS	86.195	74.687	67.995	63.908
MOLECULAR COMPOSITION	9.0947	8.7761	8.7758	8.7758
H	0.5141	0.0006	0.0000	0.0000
O	0.0377	0.0000	0.0000	0.0000
F	0.0064	0.0000	0.0000	0.0000
H2	3.8318	4.0255	4.0258	4.0258
H2O	1.4735	1.5833	1.5833	1.5833
HF	3.1603	3.1667	3.1667	3.1667
O2	0.0012	0.0000	0.0000	0.0000
OH	0.0998	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000

TABLE 7

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	H2O2	89.500		1.443	298.16
	H2	10.500		710.0E-4	20.400
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	H2O2		-44.840		
	H2		-1.8870		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	15.6789			
	O	5.2622			
PROPELLANT ENTHALPY		-127.81	KCAL/100 GM		
PROPELLANT DENSITY		0.4764	GM/CC		
	CHAMBER	1000.0	EXHAUST		
			14.70	0.0172	LB/CU IN
PRESSURE (PSI)				2.000	EXHAUST
SHIFTING EQUILIBRIA					0.2000
ISP (SEC)					383.22
IVSP(LB-SEC/CU IN)					6.5960
TEMPERATURE (K)					422.73
CP (CAL/GM-DEG.K)					0.61499
MOL. WT.-EFFECTIVE					12.756
CP/CV -EFFECTIVE					1.3393
CF -APPROX.					1.8903
PEAE/M (SEC)					7.4765
AE/AT -APPROX.					184.40
FROZEN EQUILIBRIA					
ISP (SEC)					382.21
TEMPERATURE (K)					412.15
C* (FT/SEC)					
CF (SEC)					1.7690
PEAE/M (SEC)					7.3212
AE/AT					180.57

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	14.70	0.2000
2567.1	1163.8	743.88	422.73
-127.81	-246.87	-276.13	-296.59
415.77	415.77	415.77	415.77
88.558	77.000	66.076	61.498
7.8529	7.8394	7.8394	7.8394
	0.0182	0.0000	0.0000
	0.0000	0.0000	0.0000
	2.5725	2.5772	2.5772
	5.2536	5.2622	5.2622
	0.0000	0.0000	0.0000
	0.0085	0.0000	0.0000

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
O
H2
H2O
O2
OH

TABLE 9

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	N2O4	87.000		1.430	298.16
	H2	13.000		710.0F-4	20.400
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
N2O4	N2O4	-5.4000			
H2	H2	-1.8870			
ATOMIC COMPOSITION (GM AT/100GM)					
H		12.8968			
N		1.8910			
O		3.7820			
PROPELLANT ENTHALPY		-17.274 KCAL/100 GM			
PROPELLANT DENSITY		0.4099 GM/CC			
	CHAMBER	1000.0			
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)					
IVSP (LB-SEC/CU IN)					
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAE/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAE/M (SEC)					
AE/AT					

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3028.8	1392.1	889.15	503.75
-17.274	-151.08	-184.01	-207.04
403.95	403.95	403.95	403.95
81.011	69.734	62.364	57.345
7.4660	7.3939	7.3938	7.3915
0.0926	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0010	0.0000	0.0000	0.0000
2.6478	2.6664	2.6663	2.6628
3.7307	3.7820	3.7820	3.7820
0.0006	0.0000	0.0000	0.0000
0.0462	0.0000	0.0000	0.0000
0.9438	0.9455	0.9454	0.9443
0.0029	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0002	0.0000	0.0001	0.0024

509

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR
	NF3	94.500	
	H2	5.5000	
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY
NF3	NF3	-32.000	1.532
H2	H2	-1.8870	710.0E-4
ATOMIC COMPOSITION(GM AT/100GM)			
H	5.4563		
N	1.3308		
F	3.9925		
PROPELLANT ENTHALPY			
PROPELLANT DENSITY			
	-47.735 KCAL/100 GM		
	0.7186 GM/CC		
	CHAMBER		
	1000.0		
PRESSURE (PSI)			
SHIFTING EQUILIBRIA			
ISP (SEC)			
IVSP(LB-SEC/CU IN)			
TEMPERATURE (K)			
CP (CAL/GM-DEG.K)			
MOL. WT.-EFFECTIVE			
CP/CV -EFFECTIVE			
CF -APPROX.			
PEAE/M (SEC)			
AE/AT -APPROX.			
FROZEN EQUILIBRIA			
ISP (SEC)			
TEMPERATURE (K)			
C* (FT/SEC)			
CF (SEC)			
PEAE/M (SEC)			
AE/AT			

CASE
GASIS: 100 GM PROPELLANT

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4212.3	1969.0	1185.3	627.54
-47.735	-188.99	-222.21	-243.91
301.17	301.17	301.17	301.17
49.527	44.280	39.784	37.821
5.6807	5.3911	5.3898	5.3898
0.4796	0.0026	0.0000	0.0000
0.0009	0.0000	0.0000	0.0000
0.1015	0.0000	0.0000	0.0000
0.5424	0.7306	0.7319	0.7319
3.8910	3.9925	3.9925	3.9925
0.6646	0.6654	0.6654	0.6654
0.0007	0.0000	0.0000	0.0000
0.0002	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

TABLE 13

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLF3	93.500		1.810	298.16
	H2	6.5000		710.0E-4	20.400
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	CLF3		-44.400		
	H2		-1.8870		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	6.4484			
	F	3.0338			
	CL	1.0113			
	PROPELLANT ENTHALPY	-50.985	KCAL/100 GM		
	PROPELLANT DENSITY	0.6983	GM/CC		
	CHAMBER	1000.0	EXHAUST	0.0252	LB/CU IN
	EXHAUST	14.70	EXHAUST	2.000	0.2000
	PRESSURE (PSI)				
	SHIFTING EQUILIBRIA				
	ISP (SEC)		317.88	351.71	371.85
	IVSP(LB-SEC/CU IN)		8.0200	8.8735	9.3816
	TEMPERATURE (K)		1601.4	946.58	494.71
	CP (CAL/GM-DEG.K)	3689.6	0.41265	0.37959	0.36714
	MOL. WT.-EFFECTIVE	0.47511	19.059	19.059	19.059
	CP/CV -EFFECTIVE	18.364	1.3381	1.3787	1.3966
	CF -APPROX.	1.2950	1.6072	1.7782	1.8800
	PEAF/M (SEC)		22.853	12.208	6.0350
	AE/AT -APPROX.		7.8620	30.862	152.56
	FROZEN EQUILIBRIA				
	ISP (SEC)		304.20	339.22	355.36
	TEMPERATURE (K)		1307.4	643.78	298.16
	C* (FT/SEC)	3689.6			
	CF (SEC)	6363.8	1.5380	1.7150	1.7966
	PEAF/M (SEC)		20.234	8.9349	3.9502
	AE/AT		6.9611	22.587	99.858

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	1601.4	946.58	494.71
ENTHALPY (KILOCALORIES)	-167.12	-193.15	-209.90
ENTROPY (CALORIES/DEG.K)	282.07	282.07	282.07
HEAT CAPACITY (CAL/K)	47.511	37.959	36.714
MOLES OF GAS	5.4455	5.2468	5.2468
MOLECULAR COMPOSITION:			
H	0.0001	0.0000	0.0000
F	0.0000	0.0000	0.0000
CL	0.0001	0.0000	0.0000
H2	1.1344	1.2016	1.2016
HCL	0.8914	1.0113	1.0113
HF	3.0218	3.0338	3.0338
F2	0.0000	0.0000	0.0000
CL2	0.0004	0.0000	0.0000
CLF	0.0000	0.0000	0.0000

TABLE 15

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLO3F	89.000		1.430	298.16
	H2	11.000		710.0E-4	20.400
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	CLO3F	-10.100			
	H2	-1.8870			
ATOMIC COMPOSITION(GM AT/100GM)					
H	10.9127				
O	2.6060				
F	0.8686				
CL	0.8686				
PROPELLANT ENTHALPY		KCAL/100 GM			
		0.4605			
PROPELLANT DENSITY	CHAMBER	GM/CC			
	1000.0	14.70			
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)				0.0166	LB/CU IN
IVSP(LB-SEC/CU IN)				EXHAUST	EXHAUST
TEMPERATURE (K)				2.000	0.2000
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF (SEC)					
PEAF/M (SEC)					
AE/AT					

TABLE 16

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.070	0.2000
3388.7	1655.8	1070.6	605.83
-19.070	-152.90	-187.14	-210.88
358.00	358.00	358.00	358.00
67.736	59.400	53.582	48.799
6.5127	6.3252	6.3250	6.3250
0.1971	0.0003	0.0000	0.0000
0.0064	0.0000	0.0000	0.0000
0.0010	0.0000	0.0000	0.0000
0.0466	0.0001	0.0000	0.0000
1.9756	1.9816	1.9817	1.9817
2.4818	2.6059	2.6060	2.6060
0.8218	0.8686	0.8686	0.8686
0.8677	0.8686	0.8686	0.8686
0.0032	0.0000	0.0000	0.0000
0.1112	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
O
F
CL
H2
H2O
HCL
HF
O2
OH
F2
CL2
CLO
CLF

515

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR
	NO2CLO4	91.000	
	H2	9.0000	
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	
	NO2CLO4	8.0000	
	H2	-1.8870	
ATOMIC COMPOSITION(GM AT/100GM)		DENSITY	REF. TEMP.
H	8.9286	2.220	298.16
N	0.6256	710.0E-4	20.400
O	3.7535		
CL	0.6256		
	-3.4195 KCAL/100 GM		
PROPELLANT ENTHALPY		0.0215 LB/CU IN	
PROPELLANT DENSITY	CHAMBER	EXHAUST	EXHAUST
	1000.0	2.000	0.2000
PRESSURE (PSI)			
SHIFTING EQUILIBRIA			
ISP (SEC)	333.45	380.36	413.84
IVSP(LB-SEC/CU IN)	7.1818	8.1922	8.9132
TEMPERATURE (K)	2238.1	1585.9	1009.1
CP (CAL/GM-DEG.K)	0.57642	0.53427	0.47112
MOL. WT.-EFFECTIVE	19.578	19.646	19.647
CP/CV -EFFECTIVE	1.2137	1.2335	1.2734
CF -APPROX.	1.6740	1.9094	2.0775
PEAF/M (SEC)	29.640	18.349	10.731
AE/AT -APPROX.	10.125	46.057	269.34
FROZEN EQUILIBRIA			
ISP (SEC)	314.84	358.57	385.28
TEMPERATURE (K)	1609.8	973.73	465.44
C* (FT/SEC)			
CF (SEC)	1.5805	1.8000	1.9341
PEAF/M (SEC)	24.305	12.909	5.7426
AE/AT	8.3025	32.402	144.14

TABLE 18

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3540.9	2238.1	1585.9	1009.1
TEMPERATURE (KELVIN)	-3.4195	-131.21	-169.69	-200.24
ENTHALPY (KILOCALORIES)	327.42	327.42	327.42	327.42
ENTROPY (CALORIES/DEG.K)	61.913	57.642	53.427	47.112
HEAT CAPACITY (CAL/K)	5.4982	5.1076	5.0901	5.0899
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.1572	0.0100	0.0002	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0412	0.0002	0.0000	0.0000
CL	0.0677	0.0086	0.0002	0.0000
H2	0.7362	0.4070	0.3980	0.3980
H2O	3.2028	3.7368	3.7534	3.7535
HCL	0.5574	0.6169	0.6254	0.6256
O2	0.0714	0.0009	0.0000	0.0000
OH	0.3358	0.0140	0.0001	0.0000
N2	0.2975	0.3125	0.3128	0.3128
NO	0.0307	0.0006	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CL2	0.0002	0.0000	0.0000	0.0000
CL0	0.0001	0.0000	0.0000	0.0000

TABLE 19

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	NH ₄ ClO ₄	95.500		1.960	293.16
	H ₂	4.5000		710.0E-4	20.400
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	NH ₄ ClO ₄	-69.420			
	H ₂	-1.8970			
ATOMIC COMPOSITION (GM AT/100GM)					
	H	7.7154			
	N	0.8128			
	O	3.2511			
	CL	0.8128			
PROPELLANT ENTHALPY		-60.636	KCAL/100 GM		
PROPELLANT DENSITY		0.8920	GM/CC		
PRESSURE (PSI)	CHAMBER	1000.0	EXHAUST	0.0322	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	0.2000
ISP (SEC)					
IVSP (LB-SEC/CU IN)					
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF (SEC)					
PEAF/M (SEC)					
AE/AT					

TABLE 20

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3040.3	1571.8	1061.9	628.91
TEMPERATURE (KELVIN)	-60.636	-151.06	-175.79	-193.55
ENTHALPY (KILOCALORIES)	283.66	283.66	283.66	283.66
ENTROPY (CALORIES/DEG.K)	54.774	48.449	43.419	38.647
HEAT CAPACITY (CAL/K)	4.7787	4.6706	4.6705	4.6705
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0261	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0048	0.0000	0.0000	0.0000
CL	0.0374	0.0001	0.0000	0.0000
H2	0.3076	0.2002	0.2002	0.2002
H2O	3.1030	3.2511	3.2511	3.2511
HCL	0.7748	0.8127	0.8128	0.8128
O2	0.0194	0.0000	0.0000	0.0000
OH	0.0932	0.0000	0.0000	0.0000
N2	0.4007	0.4064	0.4064	0.4064
NO	0.0113	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CL2	0.0003	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000

TABLE 21

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	O ₂	53.000		1.142	90.200
	N ₂ H ₄	47.000		1.004	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	O ₂	-3.0800			
	N ₂ H ₄	12.050			
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.8662			
N		2.9331			
O		3.3125			
PROPELLANT ENTHALPY		KCAL/100 GM			
PROPELLANT DENSITY		GM/CC			
	CHAMBER	1.073	EXHAUST	0.0388	LB/CU IN
	1000.0		14.70	2.000	EXHAUST
					0.2000
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)		30.29		345.47	374.32
IVSP(LB-SEC/CU IN)		11.793		13.389	14.507
TEMPERATURE (K)		2007.3		1393.8	860.49
CP (CAL/GM-DEG.K)		0.49750		0.46526	0.40448
MOL. WT.-EFFECTIVE		21.757		21.789	21.790
CP/CV -EFFECTIVE		1.2249		1.2438	1.2911
CF -APPROX.		1.6630		1.8891	2.0458
PEAF/M (SEC)		26.214		16.009	9.1213
AE/AT -APPROX.		9.7491		43.747	249.26
FROZEN EQUILIBRIA					
ISP (SEC)		288.83		328.82	352.59
TEMPERATURE (K)		1529.0		908.35	434.01
C* (FT/SEC)		3398.2			
CF (SEC)		5886.8			
PEAF/M (SEC)				1.7971	1.9271
AE/AT				11.576	5.1580
				31.633	140.95

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3398.2	2007.3	1393.8	860.49
12.571	-93.840	-124.59	-148.46
294.26	294.26	294.26	294.26
53.617	49.750	46.526	40.448
4.8468	4.5963	4.5894	4.5894
0.0602	0.0002	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0428	0.0006	0.0000	0.0000
0.2368	0.0046	0.0000	0.0000
2.5213	2.9201	2.9329	2.9331
0.1822	0.1823	0.1891	0.1897
0.2896	0.0166	0.0004	0.0000
1.4193	1.4613	1.4661	1.4665
0.0943	0.0104	0.0010	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
N
O
H2
H2O
O2
OH
N2
NO
NH
NH2
NH3

TABLE 23

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	HEAT OF FORM.	DENSITY	REF. TEMP.
	F2	55.000		-3.4670	1.510	85.200
	N2H4	45.000		12.050	1.004	298.16
	INGREDIENT DATA:	FORMULA				
	F2					
	N2H4					
	ATOMIC COMPOSITION(GM AT/100GM)					
	H	5.6166				
	N	2.8083				
	F	2.8947				
	PROPELLANT ENTHALPY	11.902	KCAL/100 GM			
	PROPELLANT DENSITY	1.231	GM/CC			
	CHAMBER					
	1000.0					
	PRESSURE (PSI)					
	SHIFTING EQUILIBRIA					
	ISP (SEC)					
	IVSP(LB-SEC/CU IN)					
	TEMPERATURE (K)					
	CP (CAL/GM-DEG.K)					
	MOL. WT.-EFFECTIVE					
	CP/CV -EFFECTIVE					
	CF -APPROX.					
	PEAF/M (SEC)					
	AE/AT -APPROX.					
	FROZEN EQUILIBRIA					
	ISP (SEC)					
	TEMPERATURE (K)					
	C* (FT/SEC)					
	CF (SEC)					
	PEAF/M (SEC)					
	AE/AT					

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	3959.2	1769.3	1057.7	559.37
ENTROPY (CALORIES/DEG.K)	11.902	-124.03	-155.19	-175.52
HEAT CAPACITY (CAL/K)	311.73	311.73	311.73	311.73
MOLES OF GAS	51.650	46.135	42.172	39.781
MOLECULAR COMPOSITION:	5.9057	5.6602	5.6598	5.6594
H	0.4648	0.0008	0.0000	0.0000
N	0.0005	0.0000	0.0000	0.0000
F	0.0268	0.0000	0.0000	0.0000
H2	1.1411	1.3605	1.3609	1.3603
HF	2.8679	2.8947	2.8947	2.8947
N2	1.4033	1.4041	1.4041	1.4039
NH	0.0008	0.0000	0.0000	0.0000
NH2	0.0004	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0004
F2	0.0000	0.0000	0.0000	0.0000

TABLE 25

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	N2H4	40.000		1.074	298.16
	OF2	60.000		1.530	128.00
INGREDIENT DATA:	N2H4	HEAT OF FORM.			
	OF2	12.050			
ATOMIC COMPOSITION (GM AT/100GM)		3.6000			
	H	4.9925			
	N	2.4962			
	O	1.1111			
	F	2.2222			
PROPELLANT ENTHALPY		19.040	KCAL/100 GM		
PROPELLANT DENSITY		1.265	GM/CC		
PRESSURE (PSI)		100.0	CHAMBER		
SHIFTING EQUILIBRIA			EXHAUST		
ISP (SEC)			14.70	0.0457	LB/CU IN
IVSP (LB-SEC/CU IN)				EXHAUST	0.2000
TEMPERATURE (K)				390.58	420.39
CP (CAL/GM-DEG.K)		4036.6		17.850	19.212
MOLE WT.-EFFECTIVE		0.49250		1606.3	926.54
GP/CV -EFFECTIVE		18.718		0.42928	0.38273
GP -APPROX.		1.2748		20.595	20.595
PEAE/M (SEC)				1.1900	1.3371
AE/AT -APPROX.				1.8955	2.0402
FROZEN EQUILIBRIA				17.265	9.2522
ISP (SEC)				41.895	224.51
TEMPERATURE (K)				350.13	379.95
C* (FT/SEC)		4036.6		806.38	315.81
CF (SEC)		6629.5		1.7380	1.8439
PEAE/M (SEC)				10.400	3.8391
AE/AT				25.236	93.159

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2415.0	1606.3	926.54
ENTHALPY (KILOCALORIES)	-117.74	-156.28	-184.07
ENTROPY (CALORIES/DEG.K)	302.01	302.01	302.01
HEAT CAPACITY (CAL/K)	45.908	42.928	36.273
MOLES OF GAS	4.8759	4.8556	4.8555
MOLECULAR COMPOSITION:			
H	0.0196	0.0002	0.0000
N	0.0000	0.0000	0.0000
O	0.0007	0.0000	0.0000
F	0.0003	0.0000	0.0000
H2	0.2768	0.2740	0.2740
H2O	1.0911	1.1111	1.1111
HF	2.2220	2.2222	2.2222
O2	0.0012	0.0000	0.0000
OH	0.0150	0.0000	0.0000
N2	1.2472	1.2481	1.2481
NO	0.0019	0.0000	0.0000
F2	0.0000	0.0000	0.0000

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CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	H2O2	67.000		1.443	298.16
	N2H4	33.000		1.004	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	H2O2		-44.840		
	N2H4		12.050		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	8.0581			
	N	2.0594			
	O	3.9393			
	PROPELLANT ENTHALPY	-75.912	KCAL/100 GM		
	PROPELLANT DENSITY	1.261	GM/CC		
	CHAMBER		EXHAUST		
	1000.0		14.70		
	PRESSURE (PSI)			0.0456	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	EXHAUST
	ISP (SEC)			2.000	0.2000
	IVSP(LB-SEC/CU IN)	286.01			
	TEMPERATURE (K)	13.031			
	CP (CAL/GM-DEG.K)	1517.3			
	MOL. WT.-EFFECTIVE	2923.2			
	CP/CV -EFFECTIVE	0.60702			
	CF -APPROX.	19.398			
	PEAF/M (SEC)	1.2030			
	AE/AT -APPROX.				
	FROZEN EQUILIBRIA				
	ISP (SEC)				
	TEMPERATURE (K)	276.84			
	C* (FT/SEC)	2923.2			
	CF (SEC)	5657.6			
	PEAF/M (SEC)				
	AE/AT				

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	2923.2	1517.3	1030.7	616.20
ENTROPY (CALORIES/DEG.K)	-75.912	-169.92	-195.96	-214.71
HEAT CAPACITY (CAL/K)	306.23	306.23	306.23	306.23
MOLES OF GAS	60.702	53.716	47.937	42.536
MOLECULAR COMPOSITION:	5.1550	5.0588	5.0588	5.0588
H	0.0156	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0041	0.0000	0.0000	0.0000
H2	0.2098	0.0898	0.0897	0.0897
H2O	3.7664	3.9393	3.9393	3.9393
O2	0.0298	0.0000	0.0000	0.0000
OH	0.0900	0.0000	0.0000	0.0000
N2	1.0200	1.0297	1.0297	1.0297
NO	0.0193	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000

TABLE 29

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	N2O4	57.000		1.430	298.16
	N2H4	43.000		1.004	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	N2O4	N2O4	-5.4000		
	N2H4	N2H4	12.050		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	5.3669			
	N	3.9224			
	O	2.4778			
	PROPELLANT ENTHALPY	12.823 KCAL/100 GM			
	PROPELLANT DENSITY	1.209 GM/CC			
	CHAMBER	1000.0			
	EXHAUST	14.70			
	0.0437 LB/CU IN				
	EXHAUST	2.000			
	0.2000				
	352.33				
	15.394				
	667.66				
	0.37794				
	21.530				
	1.3231				
	1.9809				
	7.6096				
	213.92				
	338.46				
	435.98				
	1.9029				
	5.3424				
	150.18				
	291.41				
	12.733				
	1704.4				
	0.47299				
	21.529				
	1.2425				
	1.6384				
	23.487				
	8.9856				
	280.14				
	1437.8				
	1.5751				
	21.285				
	8.1433				
	3256.9				
	5722.6				
	ISP (SEC)				
	IVSP(LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)				
	MOL. WT.-EFFECTIVE				
	CP/CV -EFFECTIVE				
	CF -APPROX.				
	PEAF/M (SEC)				
	AE/AT -APPROX.				
	FROZEN EQUILIBRIA				
	ISP (SEC)				
	TEMPERATURE (K)				
	C* (FT/SEC)				
	CF (SEC)				
	PEAF/M (SEC)				
	AE/AT				

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
H	1000.0	14.70	2.070	0.2000
N	3256.9	1704.4	1135.4	667.66
O	12.823	-84.774	-111.02	-129.84
H2	284.35	284.35	284.35	284.35
H2O	51.812	47.299	42.557	37.794
O2	4.7970	4.6448	4.6447	4.6447
OH	0.0515	0.0001	0.0000	0.0000
N2	0.0000	0.0000	0.0000	0.0000
NO	0.0114	0.0000	0.0000	0.0000
NH	0.3546	0.2056	0.2056	0.2056
NH2	2.2361	2.4777	2.4778	2.4778
NH3	0.0290	0.0000	0.0000	0.0000
	0.1340	0.0001	0.0000	0.0000
	1.9419	1.9612	1.9612	1.9612
	0.0384	0.0000	0.0000	0.0000
	0.0001	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000

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CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	REF. TEMP.
NF3		77.000		144.00
N2H4		23.000		298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	
NF3	NF3	-32.000	1.532	
N2H4	N2H4	12.050	1.004	
ATOMIC COMPOSITION(GM AT/100GM)				
H	2.8707			
N	2.5197			
F	3.2532			
PROPELLANT ENTHALPY		KCAL/100 GM		
PROPELLANT DENSITY		GM/CC		
	CHAMBER	EXHAUST		
	1000.0	14.70		
PRESSURE (PSI)				
SHIFTING EQUILIBRIA				
ISP (SEC)		305.28		
IVSP(LB-SEC/CU IN)		15.074		
TEMPERATURE (K)		1644.0		
CP (CAL/GM-DEG.K)	4201.5			
MOL. WT.-EFFECTIVE	0.39536			
CP/CV -EFFECTIVE	21.823			
CF -APPROX.	1.2992			
PEAE/M (SEC)				
AE/AT -APPROX.				
FROZEN EQUILIBRIA				
ISP (SEC)		297.73		
TEMPERATURE (K)		1503.6		
C* (FT/SEC)	4201.5			
CF (SEC)	6222.1			
PEAE/M (SEC)				
AE/AT				

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4201.5	1644.0	1040.4	647.60
-26.052	-133.16	-156.69	-173.57
253.37	253.37	253.37	253.37
39.536	35.371	32.693	30.824
4.5823	4.5107	4.4372	4.3237
0.0584	0.0000	0.0000	0.0000
0.0010	0.0000	0.0000	0.0000
0.4615	0.3778	0.2309	0.0037
0.0103	0.0000	0.0000	0.0000
2.7915	2.8707	2.8707	2.8707
1.2593	1.2599	1.2599	1.2599
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0001	0.0023	0.0758	0.1894

TEMPERATURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
N
F
H2
HF
N2
NH
NH2
NH3
F2

TABLE 33

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLF3	73.000		1.810	298.16
	N2H4	27.000		1.004	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	CLF3	-44.400			
	N2H4	12.050			
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.3699			
N		1.6850			
F		2.3687			
CL		0.7896			
PROPELLANT ENTHALPY		KCAL/100 GM			
		-24.904			
PROPELLANT DENSITY		GM/CC			
		1.488			
CHAMBER					
		1000.0			
EXHAUST					
		14.70			
PRESSURE (PSI)					
		292.76			
SHIFTING EQUILIBRIA					
ISP (SEC)		15.735			
IVSP(LB-SEC/CU IN)		1798.0			
TEMPERATURE (K)		0.33706			
CP (CAL/GM-DEG.K)		24.348			
MOL. WT.-EFFECTIVE		1.3195			
CP/CV -EFFECTIVE		1.6229			
CF -APPROX.		21.808			
PEAF/M (SEC)		8.2264			
AE/AT -APPROX.		277.69			
FROZEN EQUILIBRIA					
ISP (SEC)		1387.0			
TEMPERATURE (K)		3862.0			
C* (FT/SEC)		5803.8			
CF (SEC)					
PEAF/M (SEC)					
AE/AT					

0.0537 LB/CU IN					
EXHAUST	2.000				
EXHAUST	325.22				
EXHAUST	17.479				
EXHAUST	1083.0				
EXHAUST	0.30750				
EXHAUST	24.351				
EXHAUST	1.3613				
EXHAUST	1.6029				
EXHAUST	11.823				
EXHAUST	32.770				
EXHAUST	310.48				
EXHAUST	679.16				
EXHAUST	1.7212				
EXHAUST	8.1574				
EXHAUST	22.610				

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
H	1000.0	14.70	2.0000	0.2000
N	3882.0	1798.0	1083.0	573.80
F	-24.904	-123.41	-146.46	-161.58
CL	237.91	237.91	237.91	237.91
H2	37.280	33.706	30.750	28.871
HCL	4.3133	4.1072	4.1066	4.1066
HF	0.1362	0.0002	0.0000	0.0000
N2	0.0003	0.0000	0.0000	0.0000
NH	0.0378	0.0000	0.0000	0.0000
NH2	0.2392	0.0010	0.0000	0.0000
NH3	0.1776	0.1062	0.1058	0.1058
F2	0.5476	0.7886	0.7896	0.7896
CL2	2.3306	2.3687	2.3687	2.3687
CLF	0.6422	0.6425	0.6425	0.8425
	0.0002	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000
	0.0000	0.0000	0.0000	0.0000
	0.0012	0.0000	0.0000	0.0000
	0.0002	0.0000	0.0000	0.0000

TABLE 35

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLO3F	59.500		1.430	298.16
	N2H4	40.500		1.004	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	CLO3F	-10.100			
	N2H4	12.050			
ATOMIC COMPOSITION (GM AT/100GM)					
H	5.0549				
N	2.5274				
O	1.7422				
F	0.5807				
CL	0.5807				
PROPELLANT ENTHALPY		KCAL/100 GM			
PROPELLANT DENSITY		GM/CC			
	CHAMBER	1.220			
	EXHAUST	14.70			
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)		295.16		332.14	356.68
IVSP (LB-SEC/CU IN)		13.014		14.644	15.726
TEMPERATURE (K)		1676.3		1236.1	716.55
CP (CAL/GM-DEG.K)		0.42836		0.40149	0.34701
MOL. WT.-EFFECTIVE		22.868		22.873	22.873
CP/CV -EFFECTIVE		1.2545		1.2762	1.3340
CF -APPROX.		1.6519		1.6598	1.9962
PEAE/M (SEC)		24.034		14.067	7.5934
AE/AT -APPROX.		9.1525		39.364	212.48
FROZEN EQUILIBRIA					
ISP (SEC)		279.72		316.76	336.73
TEMPERATURE (K)		1448.0		800.26	367.42
C* (FT/SEC)		3465.5			
CF (SEC)		5748.9			
PEAE/M (SEC)		1.5654		1.7725	1.8845
AE/AT		20.578		10.042	4.3373
		7.8365		28.102	121.37

TABLE 36

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3465.5	1876.3	1236.1	716.55
9.3626	-90.763	-117.42	-136.85
271.44	271.44	271.44	271.44
46.651	42.836	40.149	34.701
4.5977	4.3730	4.3719	4.3719
0.0884	0.0006	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0203	0.0000	0.0000	0.0000
0.0017	0.0000	0.0000	0.0000
0.0660	0.0010	0.0000	0.0000
0.3916	0.2050	0.2045	0.2045
1.4670	1.7417	1.7422	1.7422
0.5141	0.5797	0.5807	0.5807
0.5791	0.5807	0.5807	0.5807
0.0304	0.0000	0.0000	0.0000
0.1557	0.0004	0.0000	0.0000
1.2444	1.2637	1.2637	1.2637
0.0384	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0002	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
N
O
F
CL
H2
H2O
HCL
HF
O2
OH
N2
NO
NH
NH2
NH3
F2
CL2
CLO
CLF

TABLE 37

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	NO ₂ ClO ₄	56.000		2.220	298.16
	N ₂ H ₄	44.000		1.004	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	NO ₂ ClO ₄	8.0000			
	N ₂ H ₄	12.050			
ATOMIC COMPOSITION (GM AT/100GM)					
H		5.4918			
N		3.1308			
O		2.3098			
CL		0.3850			
PROPELLANT ENTHALPY		KCAL/100 GM			
		19.624			
PROPELLANT DENSITY		GM/CC			
		1.448			
CHAMBER					
		1000.0			
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)				0.0523	LB/CU IN
IVSP (LB-SEC/CU IN)				EXHAUST	0.2000
TEMPERATURE (K)				332.01	357.30
CP (CAL/GM-DEG.K)				17.372	18.696
MOL. WT.-EFFECTIVE				1222.1	722.02
CP/CV -EFFECTIVE				0.43128	0.36920
CF -APPROX.				22.204	22.204
PEAE/M (SEC)				1.2619	1.3200
AE/AT -APPROX.				1.8576	1.9991
FROZEN EQUILIBRIA					
ISP (SEC)				14.333	7.8686
TEMPERATURE (K)				40.096	220.12
C* (FT/SEC)				319.35	340.54
CF (SEC)				844.27	407.70
PEAE/M (SEC)				1.7867	1.9053
AE/AT				10.746	4.8662
				30.060	136.13

TABLE 38

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3363.4	1824.7	1222.1	722.02
19.624	-80.159	-107.06	-127.10
279.61	279.61	279.61	279.61
50.080	45.947	43.128	36.920
4.7012	4.5044	4.5038	4.5038
0.0725	0.0004	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0157	0.0000	0.0000	0.0000
0.0345	0.0004	0.0000	0.0000
0.4187	0.2437	0.2436	0.2436
2.0377	2.3095	2.3098	2.3098
0.3502	0.3846	0.3850	0.3850
0.0306	0.0000	0.0000	0.0000
0.1560	0.0003	0.0000	0.0000
1.5458	1.5654	1.5654	1.5654
0.0391	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
N
O
CL
H2
H2O
HCL
O2
OH
N2
NO
NH
NH2
NH3
CL2
CLO

TABLE 40

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.070	0.2000
2956.5	1503.1	987.82	583.09
-34.912	-114.68	-135.47	-150.49
259.62	259.62	259.62	259.62
48.130	43.010	38.234	34.307
4.3721	4.2733	4.2723	4.2596
0.0122	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0049	0.0000	0.0000	0.0000
0.0344	0.0015	0.0001	0.0000
0.1188	0.0001	0.0000	0.0000
2.3710	2.5185	2.5191	2.5443
0.6031	0.6361	0.6354	0.5849
0.0376	0.0170	0.0171	0.0044
0.0787	0.0003	0.0000	0.0000
1.0875	1.0990	1.0992	1.0992
0.0234	0.0004	0.0000	0.0000
0.0004	0.0003	0.0014	0.0267
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

PRESSURE (PSI)

TEMPERATURE (KELVIN)

ENTHALPY (KILOCALORIES)

ENTROPY (CALORIES/DEG.K)

HEAT CAPACITY (CAL/K)

MOLES OF GAS

MOLECULAR COMPOSITION:

H
N
O
CL
H2
H2O
HCL
O2
OH
N2
NO
CL2
CLO
NH
NH2
NH3

TABLE 41

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	UDMH	50.000		0.7860	298.16
	O2	50.000		1.142	90.200
INGREDIENT DATA:	C2N2H8		HEAT OF FORM.		
	UDMH		12.740		
	O2		-3.0800		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	6.6556			
	C	1.6639			
	N	1.6639			
	O	3.1250			
PROPELLANT ENTHALPY		5.7865	KCAL/100 GM		
PROPELLANT DENSITY		0.9311	GM/CC		
	CHAMBER		EXHAUST		
	1000.0		14.70		
PRESSURE (PSI)				0.0336	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	0.2000
ISP (SEC)				321.43	344.96
IVSP(LB-SEC/CU IN)				10.814	11.672
TEMPERATURE (K)				853.11	703.58
CP (CAL/GM-DEG.K)				0.47934	0.44370
MOL. WT.-EFFECTIVE				17.424	18.541
CP/CV -EFFECTIVE				1.3122	1.3006
CF -APPROX.				1.7547	1.8941
PEAF/M (SEC)				13.170	9.4558
AE/AT -APPROX.				35.947	254.10
FROZEN EQUILIBRIA					
ISP (SEC)				317.58	336.71
TEMPERATURE (K)				682.75	353.77
C# (FT/SEC)					
CF				1.7337	1.8381
PEAF/M (SEC)				10.874	5.3142
AE/AT				29.681	145.06

TABLE 42

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
Basis: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	2877.3	1224.3	853.11	703.58
TEMPERATURE (KELVIN)	5.7865	-89.834	-112.95	-132.57
ENTHALPY (KILOCALORIES)	317.67	317.67	317.67	317.67
ENTROPY (CALORIES/DEG.K)	57.628	51.337	47.634	46.370
HEAT CAPACITY (CAL/K)	5.8503	5.8233	5.7792	5.5934
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0440	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0001	0.0000	0.0000	0.0000
H2	1.9936	2.2741	2.5025	2.3332
H2O	1.3073	1.0533	0.7408	0.7670
CO	1.5196	1.2559	0.6593	0.5370
CO2	0.1442	0.4079	0.7624	1.0105
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0090	0.0000	0.0000	0.0000
N2	0.8315	0.8319	0.8319	0.6319
NO	0.0005	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0001	0.0421	0.1137
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0001	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0002	0.0001	0.0002	0.0001
CONDENSED PHASES				
C/SOLID/	0	0	0	0.2027

541

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
UDMH		27.000		0.7660	298.16
F2		73.000		1.510	85.200
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
UDMH	C2N2H8	12.740			
F2	F2	-3.4670			
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.5940			
C		0.8985			
N		0.8985			
F		3.8421			
PROPELLANT ENTHALPY		-0.93683 KCAL/100 GM			
PROPELLANT DENSITY	CHAMBER	1.209 GM/CC			
	1000.0	EXHAUST	14.70	0.0437 LB/CU IN	EXHAUST
				2.000	0.2000
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)		340.25		389.12	424.31
IVSP(LB-SEC/CU IN)		14.866		17.001	18.538
TEMPERATURE (K)		2800.1		2146.2	1366.6
CP (CAL/GM-DEG.K)		0.41825		0.40354	0.37302
MOL. WT.-EFFECTIVE		23.474		24.226	24.359
CP/CV -EFFECTIVE		1.2633		1.2551	1.2799
CF -APPROX.		1.7105		1.9562	2.1331
PEAF/M (SEC)		30.310		19.684	11.432
AE/AT -APPROX.		10.369		49.478	287.35
FROZEN EQUILIBRIA					
ISP (SEC)		309.12		348.29	369.08
TEMPERATURE (K)		1690.8		897.04	391.09
C* (FT/SEC)		4314.2			
CF		6400.0			
PEAF/M (SEC)		1.5540		1.7509	1.8554
AE/AT		21.890		10.307	4.2406
		7.4881		25.908	106.59

TABLE 44

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4314.2	2800.1	2146.2	1366.6
TEMPERATURE (KELVIN)	-0.93683	-133.99	-174.96	-207.85
ENTHALPY (KILOCALORIES)	264.13	264.13	264.13	264.13
ENTROPY (CALORIES/DEG.K)	44.128	41.825	40.354	37.302
HEAT CAPACITY (CAL/K)	4.6287	4.2601	4.1279	4.1053
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.1096	0.0022	0.0000	0.0000
C	0.0203	0.0000	0.0000	0.0000
N	0.0006	0.0000	0.0000	0.0000
F	0.4601	0.1929	0.0252	0.0000
H2	0.0254	0.0002	0.0000	0.0000
HF	3.2980	3.5899	3.5939	3.5940
N2	0.2468	0.4434	0.4491	0.4492
F2	0.0001	0.0000	0.0000	0.0000
CH	0.0005	0.0000	0.0000	0.0000
CH2	0.0012	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0281	0.0003	0.0000	0.0000
CF2	0.0195	0.0035	0.0003	0.0000
CF3	0.0052	0.0125	0.0140	0.0001
CF4	0.0001	0.0036	0.0451	0.0619
CN	0.2890	0.0096	0.0002	0.0000
C2N2	0.0083	0.0002	0.0000	0.0000
C2H2	0.0176	0.0000	0.0000	0.0000
CHF3	0.0001	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0975	0.0016	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0.3843	0.8668	0.6389	0.8364

TABLE 45

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	UDMH	28.000		0.7860	298.16
	OF2	72.000		1.530	128.00
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	UDMH	C ₂ H ₂	12.740		
	OF2	OF2	3.6000		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	3.7271			
	C	0.9318			
	N	0.9318			
	O	1.3333			
	F	2.6667			
	PROPELLANT ENTHALPY	10.735	KCAL/100 GM		
	PROPELLANT DENSITY	1.209	CM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
	PRESSURE (PSI)			0.0437	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	0.2000
	ISP (SEC)			390.36	425.29
	IVSP(LB-SEC/CU IN)			17.342	18.628
	TEMPERATURE (K)			1714.9	992.53
	CP (CAL/GM-DEG.K)	4458.0		0.34120	0.35926
	MOL. WT.-EFFECTIVE	0.44360		21.764	21.765
	CP/CV -EFFECTIVE	19.623		1.3045	1.3407
	CF -APPROX.	1.2957		1.8875	2.0275
	PEAF/M (SEC)			17.156	9.2488
	AE/AT -APPROX.			40.822	219.94
	FROZEN EQUILIBRIA			362.06	382.76
	ISP (SEC)			615.76	305.22
	TEMPERATURE (K)	4458.0			
	C* (FT/SEC)	6764.7			
	CF			1.7220	1.6204
	PEAF/M (SEC)			9.9003	3.5126
	AE/AT			23.544	83.532

TABLE 46

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
3A13: 100 GM PROPELLANT	1000.0	14.70	2.030	0.2000
PRESSURE (PSI)	4458.0	2596.6	1714.9	992.53
TEMPERATURE (KELVIN)	10.735	131.13	-170.27	-193.11
ENTHALPY (KILOCALORIES)	287.16	287.16	287.16	287.16
ENTROPY (CALORIES/DEG.K)	44.360	41.507	39.120	35.926
HEAT CAPACITY (CAL/K)	5.0948	4.6223	4.5948	4.5946
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.4442	0.0404	0.0025	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0014	0.0000	0.0000	0.0000
O	0.1090	0.0010	0.0000	0.0000
F	0.1629	0.0011	0.0000	0.0000
H2	0.2500	0.2583	0.2993	0.4102
H2O	0.0829	0.2573	0.4306	0.1200
HF	2.5037	2.6655	2.6667	2.6667
CO	0.6961	0.8004	0.7609	0.6502
CO2	0.0356	0.1314	0.1739	0.2815
O2	0.0143	0.0604	0.0600	0.0000
OH	0.1126	0.0099	0.0000	0.0000
N2	0.4483	0.4654	0.4659	0.4659
NO	0.0320	0.0010	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0000	0.0000	0.0000	0.0000
CF2	0.0000	0.0000	0.0000	0.0000
CF3	0.0000	0.0000	0.0000	0.0000
CF4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
COF2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0006	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID	0	0	0	0

545

CASE	PROPELLANT COMPOSITION	WEIGHT%	MULAR
	UDMH	18.000	
	H2O2	82.000	
INGREDIENT DATA:	FORMULA	H*AT OF FORM.	
	C2N2H5	12.740	
	H2O2	-44.840	
ATOMIC COMPOSITION(GM AT/100GM)			
	H	7.2173	
	C	0.5990	
	N	0.5990	
	O	4.8213	
PROPELLANT ENTHALPY	-104.28	KCAL/100 GM	
PROPELLANT DENSITY	1.254	CM/CC	
	CHAMBER	EXHAUST	
	1000.0	14.70	
PRESSURE (PSI)			
SHIFTING EQUILIBRIA			
ISP (SEC)			
IVSP(LB-SEC/CU IN)			
TEMPERATURE (K)			
CP (CAL/GM-DEG K)			
MOL. WT.-EFFECTIVE			
CP/CV -EFFECTIVE			
CF -APPROX.			
PEAE/M (SEC)			
AE/AT -APPROX.			
FROZEN EQUILIBRIA			
ISP (SEC)			
TEMPERATURE (K)			
C* (FT/SEC)			
CF			
PEAE/M (SEC)			
AE/AT			

TABLE 48

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3001.9	1789.0	1269.7	805.21
TEMPERATURE (KELVIN)	-104.28	-196.29	-223.50	-244.62
ENTHALPY (KILOCALORIES)	290.80	290.80	290.80	290.80
ENTROPY (CALORIES/DEG.K)	56.258	53.418	49.160	43.245
HEAT CAPACITY (CAL/K)	4.6966	4.5182	4.5145	4.5144
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0152	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0032	0.0000	0.0000	0.0000
H2	0.1340	0.0038	0.0000	0.0000
H2O	3.4001	3.6035	3.6086	3.6086
CO	0.1314	0.0023	0.0000	0.0000
CO2	0.4675	0.5966	0.5990	0.5990
O2	0.0956	0.0094	0.0073	0.0073
OH	0.1339	0.0026	0.0000	0.0000
N2	0.2894	0.2992	0.2995	0.2995
NO	0.0203	0.0006	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID	0	0	0	0

TABLE 49

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	UDMH	38.000		0.7860	298.16
	N2O4	62.000		1.430	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	UDMH	C2N2H8	12.740		
	N2O4	N2O4	-5.4000		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	5.0582			
	C	1.2646			
	N	2.6122			
	O	2.6952			
	PROPELLANT ENTHALPY	4.4167 KCAL/100 GM			
	PROPELLANT DENSITY	1.090 GM/CC			
	CHAMBER	14.70			
	EXHAUST				
	PRESSURE (PSI)			0.0394 LB/CU IN	
	SHIFTING EQUILIBRIA			EXHAUST	0.2000
	ISP (SEC)			2.000	
	IVSP(LB-SEC/CU IN)			305.52	327.00
	TEMPERATURE (K)			11.958	12.883
	CP (CAL/GM-DEG.K)	2905.2		851.51	676.48
	MOL. WT.-EFFECTIVE	0.51229		0.42661	0.40807
	CP/CV -EFFECTIVE	19.516		19.708	20.854
	CF -APPROX.	1.2481		1.3095	1.3047
	PEAE/M (SEC)			1.7596	1.8958
	AE/AT -APPROX.			12.307	8.5767
	FROZEN EQUILIBRIA			35.675	248.61
	ISP (SEC)			300.09	318.46
	TEMPERATURE (K)	2905.2		709.00	372.28
	C* (FT/SEC)	5549.7			
	CF			1.7397	1.3462
	PEAE/M (SEC)			10.467	5.1788
	AE/AT			30.340	150.12

TABLE 50

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	2905.2	1259.3	851.51	676.48
TEMPERATURE (KELVIN)	4.4167	-80.768	-101.46	-118.47
ENTHALPY (KILOCALORIES)	287.67	287.67	287.67	287.67
ENTROPY (CALORIES/DEG.K)	51.229	46.293	42.651	40.807
HEAT CAPACITY (CAL/K)	5.1240	5.0997	5.0741	4.7952
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0357	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0002	0.0000	0.0000	0.0000
H2	1.2475	1.4892	1.7415	1.5882
H2O	1.2577	1.0398	0.7419	0.7286
CO	1.1045	0.8737	0.5503	0.1658
CO2	0.1599	0.3909	0.7015	0.9003
O2	0.0001	0.0000	0.0000	0.0000
OH	0.0115	0.0000	0.0000	0.0000
N2	1.3054	1.3060	1.3060	1.3060
NO	0.0011	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0128	0.1060
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0001	0.0001
CONDENSED PHASES				
C/SOLID/	0	0	0	0.0924

TABLE 51

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	UDMH	28.000		0.7850	298.16
	NF3	72.000		1.532	144.00
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
UDMH	C2N2H8	12.740			
NF3	NF3	-32.000			
ATOMIC COMPOSITION (GM AT/100GM)					
H		3.7271			
C		0.9318			
N		1.9458			
F		3.0419			
PROPELLANT ENTHALPY		-26.512	KCAL/100 GM		
PROPELLANT DENSITY		1.210	GM/CC		
CHAMBER		1000.0			
EXHAUST		14.70			
PRESSURE (PSI)				0.0437	LB/CU IN
SHIFTING EQUILIBRIA				2.000	EXHAUST
ISP (SEC)				340.34	365.46
IVSP (LB-SEC/CU IN)				14.909	15.982
TEMPERATURE (K)				1295.4	750.06
CP (CAL/GM-DEG.K)				0.39233	0.35283
MOL. WT.-EFFECTIVE				22.950	22.956
CP/CV -EFFECTIVE				1.2832	1.3251
CF -APPROX.				1.8599	1.9937
PEAF/M (SEC)				14.314	7.7297
AE/AT -APPROX.				39.043	210.84
FROZEN EQUILIBRIA				324.41	345.40
ISP (SEC)				850.47	381.85
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAF/M (SEC)				1.7697	1.8842
AE/AT				10.148	4.2795
				27.681	116.73

TABLE 52

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
SIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3749.0	1976.8	1295.4	750.06
TEMPERATURE (KELVIN)	-26.512	-132.15	-160.10	-180.01
ENTHALPY (KILOCALORIES)	257.81	257.81	257.81	257.81
ENTROPY (CALORIES/DEG.K)	45.170	41.696	39.233	35.283
HEAT CAPACITY (CAL/K)	4.4774	4.3582	4.3574	4.3562
MOLES OF GAS	0.0973	0.0017	0.0000	0.0000
MOLECULAR COMPOSITION:	0.0010	0.0000	0.0000	0.0000
H	0.0002	0.0000	0.0000	0.0000
C	0.0366	0.0000	0.0000	0.0000
N	0.1450	0.3362	0.3424	0.3402
F	3.0033	3.0419	3.0419	3.0419
H2	0.7904	0.9675	0.9728	0.9729
HF	0.0000	0.0000	0.0000	0.0000
N2	0.0001	0.0000	0.0000	0.0000
F2	0.0024	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0005	0.0000	0.0000	0.0012
CF	0.0004	0.0000	0.0000	0.0000
CF2	0.0001	0.0000	0.0000	0.0000
CF3	0.0000	0.0000	0.0000	0.0000
CF4	0.1031	0.0000	0.0000	0.0000
CN	0.0080	0.0000	0.0000	0.0000
C2N2	0.0430	0.0002	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.2455	0.0107	0.0002	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES	0.4765	0.9206	0.9316	0.9306
G/SOLID/				

TABLE 53

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	UDMH	23.000		0.7860	298.16
	CLF3	77.000		1.810	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	UDMH	C2N2H8	12.740		
	CLF3	CLF3	-44.400		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	3.0616			
	C	0.7654			
	N	0.7654			
	F	2.4984			
	CL	0.8328			
	PROPELLANT ENTHALPY	-32.102	KCAL/100 GM		
	PROPELLANT DENSITY	1.393	CM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
	PRESSURE (PSI)			0.0503	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	EXHAUST
	ISP (SEC)			2.000	0.2000
	IVSP(LB-SEC/CU IN)			309.46	333.77
	TEMPERATURE (K)			15.572	15.794
	CP (CAL/GM-DEG.K)			1300.9	864.46
	MOL. WT.-EFFECTIVE	3685.1		0.32401	0.29821
	CP/CV -EFFECTIVE	0.37326		28.166	28.470
	CF -APPROX.	26.143		1.2784	1.3056
	PEAF/M (SEC)	1.2557		1.6477	1.9928
	AE/AT -APPROX.			13.697	7.6652
	FROZEN EQUILIBRIA			40.891	234.81
	ISP (SEC)			294.94	312.51
	TEMPERATURE (K)			806.12	382.36
	C* (FT/SEC)	3685.1			
	CF	5388.6			
	PEAF/M (SEC)			1.7610	1.8659
	AE/AT			9.0387	4.0462
				26.984	120.80

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3685.1	1902.7	1360.9	864.46
TEMPERATURE (KELVIN)	-32.102	-118.89	-142.16	-160.13
ENTHALPY (KILOCALORIES)	218.80	218.80	218.80	218.80
ENTROPY (CALORIES/DEG.K)	37.326	34.211	32.801	29.821
HEAT CAPACITY (CAL/K)	3.8251	3.6513	3.5504	3.5125
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0325	0.0000	0.0000	0.0000
C	0.0006	0.0000	0.0000	0.0000
N	0.0001	0.0000	0.0000	0.0000
F	0.0545	0.0003	0.0000	0.0000
CL	0.3538	0.1546	0.0188	0.0000
H2	0.0244	0.0000	0.0000	0.0000
HCL	0.4685	0.5850	0.7155	0.8298
HF	2.4376	2.4765	2.3460	2.2518
N2	0.3250	0.3827	0.3827	0.3827
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0048	0.0465	0.0492	0.0015
CLF	0.0009	0.0001	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0003	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0011	0.0000	0.0000	0.0000
CF2	0.0013	0.0000	0.0000	0.0000
CF3	0.0005	0.0000	0.0000	0.0000
CF4	0.0000	0.0004	0.0000	0.0000
CN	0.0494	0.0050	0.0381	0.0667
C2N2	0.0028	0.0000	0.0000	0.0000
C2H2	0.0065	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
HCN	0.0603	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SCLID/	0.6332	0.7599	0.7273	0.6987

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CASE		PROPELLANT COMPOSITION		WEIGHT%		MOLAR	
		UDMH	CLO3F	25.000			
		CLO3F		75.000			
INGREDIENT DATA:		FORMULA		HEAT OF FORM.		DENSITY	
		UDMH	C2N2H8		12.740	0.7860	
		CLO3F	ClO3F		-10.100	1.430	
ATOMIC COMPOSITION(GM AT/100GM)						REF. TEMP.	
		H		3.3278		298.16	
		C		0.8319		298.16	
		N		0.8319			
		O		2.1960			
		F		0.7320			
		CL		0.7320			
PROPELLANT ENTHALPY				-2.0938	KCAL/100 GM		
PROPELLANT DENSITY				1.187	GM/CC		
PRESSURE (PSI)				CHAMBER	EXHAUST	0.0429 LB/CU IN	
SHIFTING EQUILIBRIA				1000.0	14.70	EXHAUST 0.2000	
ISP (SEC)						356.89	
IVSP(LB-SEC/CU IN)						15.304	
TEMPERATURE (K)				3685.6		1028.2	
CP (CAL/GM-DEG.K)				0.39429		0.32758	
MOL. WT.-EFFECTIVE				24.965		27.444	
CP/CV -EFFECTIVE				1.2530		1.2838	
CF -APPROX.						2.0806	
PEAE/M (SEC)						9.0760	
AE/AT -APPROX.						264.55	
FROZEN EQUILIBRIA							
ISP (SEC)						322.43	
TEMPERATURE (K)				3685.6		364.07	
C* (FT/SEC)				5519.0			
CF						1.8797	
PEAE/M (SEC)						3.9102	
AE/AT						113.98	

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3685.6	2328.2	1638.0	1028.2
-2.0938	-97.851	-126.52	-148.48
243.84	243.84	243.84	243.84
39.429	37.710	35.820	32.758
4.0055	3.6687	3.6442	3.6438
0.0924	0.0066	0.0001	0.0000
0.0000	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0500	0.0004	0.0000	0.0000
0.0060	0.0001	0.0000	0.0000
0.1592	0.0276	0.0005	0.0000
0.1886	0.0965	0.1294	0.2300
0.6907	0.8410	0.8026	0.7019
0.5710	0.7042	0.7315	0.7320
0.7260	0.7320	0.7320	0.7320
0.5743	0.5238	0.2705	0.1697
0.2576	0.5082	0.5615	0.6622
0.0728	0.0017	0.0000	0.0000
0.1797	0.0100	0.0000	0.0000
0.3958	0.4154	0.4160	0.4160
0.0403	0.0011	0.0000	0.0000
0.0009	0.0001	0.0000	0.0000
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
C
N
O
F
CL
H2
H2O
HCL
HF
CO
CO2
O2
OH
N2
NO
CL2

CONDENSED PHASES
C/SOLID/

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CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	UDMH	36.000		0.7860	298.16
	NO2CLO4	64.000		2.220	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM*		
	UDMH	C2N2H8	12.740		
	NO2CLO4	NO2CLO4	8.0000		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	4.7920			
	C	1.1980			
	N	1.6380			
	O	2.6398			
	CL	0.4400			
	PROPELLANT ENTHALPY	11.151	KCAL/100 GM		
	PROPELLANT DENSITY	1.340	CM/CC		
	CHAMBER	1000.0	EXHAUST	2.000	0.0484
	PRESSURE (PSI)		14.70	EXHAUST	0.2000
	SHIFTING EQUILIBRIA				
	ISP (SEC)				
	IVSP(LB-SEC/CU IN)	282.49		315.85	335.22
	TEMPERATURE (K)	13.676		15.291	16.422
	CP (CAL/GM-DEG.K)	1527.8		1017.0	702.73
	MOL. WT.-EFFECTIVE	0.47845		0.40238	0.38139
	CP/CV -EFFECTIVE	21.194		21.595	22.003
	CF -APPROX.	1.2437		1.2061	1.5103
	PEAF/M (SEC)			1.7946	1.9273
	AE/AT -APPROX.			12.896	8.1400
	AE/AT	8.3755		36.636	231.24
	FROZEN EQUILIBRIA				
	ISP (SEC)	275.51		309.41	328.76
	TEMPERATURE (K)	1368.9		793.31	401.03
	C* (FT/SEC)				
	CF	1.5654		1.7580	1.8679
	PEAF/M (SEC)	20.269		10.456	4.9761
	AE/AT	7.8361		29.731	141.36

TABLE 58

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3276.8	1527.8	1017.6	702.73
TEMPERATURE (KELVIN)	11.151	-80.562	-103.50	-121.09
ENTHALPY (KILOCALORIES)	275.17	275.17	275.17	275.17
ENTROPY (CALORIES/DEG.K)	47.845	43.393	40.298	38.139
HEAT CAPACITY (CAL/K)	4.7194	4.6330	4.6329	4.5448
MOLES OF GAS	0.0854	0.0000	0.0000	0.0000
MOLECULAR COMPOSITION:	0.0000	0.0000	0.0000	0.0000
H	0.0000	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0027	0.0000	0.0000	0.0000
CL	0.0224	0.0000	0.0000	0.0000
H2	0.9153	1.0697	1.3012	1.5035
H2O	1.2044	1.1063	0.6747	0.3843
HCL	0.4175	0.4400	0.4400	0.4400
CO	1.0201	0.8625	0.5308	0.2524
CO2	0.1779	0.3355	0.2671	0.3016
O2	0.0014	0.0000	0.0000	0.0000
OH	0.0483	0.0000	0.0000	0.0000
N2	0.8160	0.8190	0.8190	0.8190
NO	0.0055	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES	0	0	0	0
C/SOLID	0	0	0	0

TABLE 59

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	UDMH	14.000		0.7850	298.16
	NH ₄ ClO ₄	86.000		1.060	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	C ₂ N ₂ H ₅	12.740			
	NH ₄ ClO ₄	-69.420			
ATOMIC COMPOSITION (GM AT/100GM)					
	H	4.7913			
	C	0.4659			
	N	1.1978			
	O	2.9277			
	CL	0.7319			
PROPELLANT ENTHALPY		-47.843	KCAL/100 GM		
PROPELLANT DENSITY		1.621	GM/CC		
	CHAMBER	1000.0	EXHAUST		
			14.70		
PRESSURE (PSI)				0.0586	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP (LB-SEC/CU IN)				292.79	315.79
TEMPERATURE (K)				17.146	18.495
CP (CAL/GM-DEG.K)				1159.2	707.11
MOL. WT.-EFFECTIVE				0.37401	0.33360
CP/CV -EFFECTIVE				26.134	26.134
CF -APPROX.				1.2552	1.2952
PEAF/M (SEC)				1.8675	2.0142
AE/AT -APPROX.				13.038	7.4075
FROZEN EQUILIBRIA				41.772	236.24
ISP (SEC)				281.72	301.78
TEMPERATURE (K)				822.51	412.43
C* (FT/SEC)					
CF					
PEAF/M (SEC)				1.7969	1.9248
AE/AT				10.032	4.6959
				31.993	149.76

TABLE 60

CASE		BASIS: 100 GM PROPELLANT			
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.070	0.2000
TEMPERATURE (KELVIN)		3033.6	1702.3	1159.2	707.11
ENTHALPY (KILOCALORIES)		-47.843	-124.92	-146.36	-162.45
ENTROPY (CALORIES/DEG.K)		244.05	244.05	244.05	244.05
HEAT CAPACITY (CAL/K)		44.840	41.180	37.401	33.360
MOLES OF GAS		3.9744	3.8270	3.6264	3.8264
MOLECULAR COMPOSITION:					
H		0.0135	0.0000	0.0000	0.0000
C		0.0000	0.0000	0.0000	0.0000
N		0.0000	0.0000	0.0000	0.0000
O		0.0070	0.0000	0.0000	0.0000
CL		0.0508	0.0009	0.0000	0.0000
H2		0.1028	0.0195	0.0263	0.0329
H2O		1.9017	2.0105	2.0033	1.9968
HCL		0.6798	0.7310	0.7319	0.7319
CO		0.1304	0.0148	0.0074	0.0009
CO2		0.3355	0.4511	0.4585	0.4650
O2		0.0532	0.0000	0.0000	0.0000
OH		0.0838	0.0002	0.0000	0.0000
N2		0.5877	0.5989	0.5989	0.5989
NO		0.0224	0.0000	0.0000	0.0000
CL2		0.0006	0.0000	0.0000	0.0000
ClO		0.0000	0.0000	0.0000	0.0000
CH		0.0000	0.0000	0.0000	0.0000
CH2		0.0000	0.0000	0.0000	0.0000
CH4		0.0000	0.0000	0.0000	0.0000
CN		0.0000	0.0000	0.0000	0.0000
C2N2		0.0000	0.0000	0.0000	0.0000
C2H2		0.0000	0.0000	0.0000	0.0000
HCN		0.0000	0.0000	0.0000	0.0000
NH		0.0000	0.0000	0.0000	0.0000
NH2		0.0000	0.0000	0.0000	0.0000
NH3		0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES					
C/SOLID/		0	0	0	0

TABLE 61

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CH2	29.000		0.9200	298.16
	O2	71.000		1.142	90.200
INGREDIENT DATA:	CH2		HEAT OF FORM.		
	O2		-6.3000		
			-3.0800		
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.1352			
C		2.0676			
O		4.4375			
PROPELLANT ENTHALPY		-20.273	KCAL/100 GM		
PROPELLANT DENSITY		1.067	GM/CC		
	CHAMBER		EXHAUST		
	1000.0		14.70		
PRESSURE (PSI)				0.0386	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)				340.09	369.43
TEMPERATURE (K)				13.114	14.246
CP (CAL/GM-DEG.K)		3627.6		1524.4	1022.5
MOL. WT.-EFFECTIVE		0.48655		0.43696	0.40858
CP/CV -EFFECTIVE		22.762		24.182	24.183
CF -APPROX.		1.2187		1.2316	1.2518
PEAE/M (SEC)				1.8894	2.0524
AE/AT -APPROX.				16.025	9.8943
FROZEN EQUILIBRIA				44.515	274.86
ISP (SEC)				323.93	347.92
TEMPERATURE (K)				995.09	497.92
C* (FT/SEC)		3627.6			
CF (SEC)		5791.3			
PEAE/M (SEC)				1.7996	1.9329
AE/AT				11.668	5.4358
				32.412	151.00

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3627.6	2153.2	1524.4	1022.5
-20.273	-123.30	-153.20	-177.12
273.63	273.63	273.63	273.63
48.655	46.027	43.696	40.858
4.3933	4.1396	4.1352	4.1352
0.1328	0.0062	0.0001	0.0000
0.0000	0.0000	0.0000	0.0000
0.0365	0.0000	0.0000	0.0000
0.4522	0.4971	0.6540	0.9504
1.4400	1.5661	1.4135	1.1172
1.4845	1.2664	1.1112	0.8148
0.5830	0.8012	0.9564	1.2527
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0462	0.0000	0.0000	0.0000
0.2178	0.0026	0.0000	0.0000
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
C
O
H₂
H₂O
CO
CO₂
CH
CH₂
CH₄
O₂
OH

CONDENSED PHASES
C/SOLID/

TABLE 63

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	F2	72.500		1.510	85.200
	CH2	27.500		0.9200	298.16
INGREDIENT DATA:					
	F2		HEAT OF FORM.		
	CH2		-3.4670		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	3.9213			
	C	1.9606			
	F	3.6158			
PROPELLANT ENTHALPY					
		-19.359	KCAL/100 GM		
PROPELLANT DENSITY					
		1.284	CM/CC		
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
	ISP (SEC)		EXHAUST	0.0464	LB/CU IN
	IVSP(LB-SEC/CU IN)		14.70	EXHAUST	0.2000
	TEMPERATURE (K)	4378.6		370.98	404.18
	CP (CAL/GM-DEG.K)	0.48878		17.205	18.745
	MOL. WT.-EFFECTIVE	24.058		2039.9	1338.2
	CP/CV -EFFECTIVE	1.2034		0.43602	0.40066
	CF -APPROX.			25.841	25.850
	PEAE/M (SEC)			1.2141	1.2374
	AE/AT -APPROX.			1.9199	2.0917
FROZEN EQUILIBRIA					
	ISP (SEC)			18.398	11.074
	TEMPERATURE (K)	4378.6		47.606	286.55
	C* (FT/SEC)	6216.9		349.94	378.40
	CF			1252.6	682.38
	PEAE/M (SEC)			1.5866	1.9583
	AE/AT			24.219	6.4804
				8.5287	167.69

TABLE 64

CASE					
BASIS: 100 GM PROPELLANT					
PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST	
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000	
ENTHALPY (KILOCALORIES)	4378.6	2805.0	2039.9	1338.2	
ENTROPY (CALORIES/DEG.K)	-19.359	-140.41	-177.53	-207.10	
HEAT CAPACITY (CAL/K)	249.31	249.31	249.31	249.31	
MOLES OF GAS	48.878	45.786	43.602	40.066	
MOLECULAR COMPOSITION:	4.1565	3.5916	3.5699	3.5685	
H	0.1947	0.0332	0.0026	0.0000	
C	0.0243	0.0000	0.0000	0.0000	
F	0.3123	0.0128	0.0001	0.0000	
H2	0.0736	0.0412	0.0515	0.0527	
HF	3.4599	3.8029	3.8157	3.8158	
F2	0.0000	0.0000	0.0000	0.0000	
CH	0.0009	0.0000	0.0000	0.0000	
CH2	0.0037	0.0000	0.0000	0.0000	
CH4	0.0000	0.0000	0.0000	0.0000	
CF	0.0210	0.0000	0.0000	0.0000	
CF2	0.0089	0.0000	0.0000	0.0000	
CF3	0.0015	0.0000	0.0000	0.0000	
CF4	0.0000	0.0000	0.0000	0.0000	
C2H2	0.0553	0.0013	0.0000	0.0000	
CHF3	0.0000	0.0000	0.0000	0.0000	
CH2F2	0.0000	0.0000	0.0000	0.0000	
CONDENSED PHASES					
C/SOLID/	1.7897	1.9579	1.9605	1.9606	

TABLE 65

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLES	DENSITY	REF. TEMP.
	OF2	78.000		1.530	128.00
	CH2	22.000		0.9200	298.16
INGREDIENT DATA:	OF2	CH2	HEAT OF FORM.		
			3.6000		
			-6.5000		
ATOMIC COMPOSITION(GM AT/100GM)					
H		3.1370			
C		1.5685			
O		1.4444			
F		2.5889			
PROPELLANT ENTHALPY			KCAL/100 GM		
PROPELLANT DENSITY			GM/CC	0.0482 LB/CU IN	EXHAUST
			1.335	2.000	0.2000
			CHAMBER		
			1000.0		
EXHAUST					
			14.70		
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)				389.90	416.79
IVSP(LB-SEC/CU IN)				18.809	20.107
TEMPERATURE (K)				1602.4	917.33
CP (CAL/GM-DEG.K)				0.36453	0.33556
MOL. WT.-EFFECTIVE				22.434	22.551
CP/CV -EFFECTIVE				1.3210	1.3561
CF -APPROX.				1.8810	2.0108
PEAE/M (SEC)				15.839	8.4379
AE/AT -APPROX.				38.206	203.54
FROZEN EQUILIBRIA					
ISP (SEC)				358.25	376.82
TEMPERATURE (K)				600.30	326.16
C* (FT/SEC)					
CF (SEC)				1.7283	1.8179
PEAE/M (SEC)				9.3509	3.6232
AE/AT				22.556	87.399

TABLE 66

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4564.0	2522.1	1602.4	917.33
TEMPERATURE (KELVIN)	-4.9954	-143.65	-179.70	-204.64
ENTHALPY (KILOCALORIES)	271.84	271.84	271.84	271.84
ENTROPY (CALORIES/DEG.K)	41.949	39.055	36.453	33.556
HEAT CAPACITY (CAL/K)	4.8415	4.4678	4.4574	4.4343
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.3291	0.0198	0.0001	0.0000
C	0.0617	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
F	0.3134	0.0011	0.0000	0.0000
H2	0.1080	0.1147	0.1240	0.1231
H2O	0.0000	0.0000	0.0000	0.0009
HF	2.5754	2.8878	2.8889	2.8889
CO	1.4444	1.4444	1.4444	1.3992
CO2	0.0000	0.0000	0.0000	0.0222
CH	0.0023	0.0000	0.0000	0.0000
CH2	0.0070	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0.0530	0.1240	0.1241	0.1472

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CASE		PROPELLANT COMPOSITION		WEIGHT%	MOLAR	INGREDIENT DATA:		HEAT OF FORM.	DENSITY	REF. TEMP.
		H2O2	CH4	86.500			H2O2	-44.840	1.043	298.16
				13.500			CH2	-6.3000	0.9200	298.16
ATOMIC COMPOSITION(GM AT/100GM)										
		H		7.0108						
		C		0.9625						
		O		5.0858						
PROPELLANT ENTHALPY				-120.28	KCAL/100 GM					
PROPELLANT DENSITY				1.340	GM/CC					
PRESSURE (PSI)				1000.0						
SHIFTING EQUILIBRIA										
ISP (SEC)									0.0484	LB/CU IN
IVSP(LB-SEC/CU IN)									EXHAUST	0.2000
TEMPERATURE (K)				2998.5					314.71	341.15
CP (CAL/GM-DEG.K)				0.57843					15.238	16.518
MOL. WT.-EFFECTIVE				21.857					1197.1	775.16
CP/CV -EFFECTIVE				1.1865					0.46157	0.43193
CF -APPROX.									22.382	22.382
PEAF/M (SEC)									1.2260	1.2588
AE/AT -APPROX.									1.8464	2.0232
FROZEN EQUILIBRIA									14.693	8.7772
ISP (SEC)				2998.5					43.571	260.28
TEMPERATURE (K)				5425.0					308.28	330.78
C* (FT/SEC)									971.95	586.88
CF (SEC)										
PEAF/M (SEC)									1.8293	1.9618
AE/AT									12.471	7.0180
									36.981	208.11

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.070	0.2000
ENTHALPY (KILOCALORIES)	2998.5	1676.4	1197.1	775.16
ENTROPY (CALORIES/DEG.K)	-120.28	-208.33	-234.10	-254.03
HEAT CAPACITY (CAL/K)	285.32	285.32	285.32	285.32
MOLES OF GAS	57.843	52.402	48.157	43.193
MOLECULAR COMPOSITION:	4.5752	4.4680	4.4679	4.4679
H	0.0177	0.0001	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
O	0.0058	0.0000	0.0000	0.0000
H2	0.1898	0.1945	0.2524	0.3254
H2O	3.2548	3.3108	3.2530	3.1600
CO	0.2849	0.1501	0.0922	0.0191
CO2	0.6776	0.6124	0.5703	0.4934
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0406	0.0000	0.0000	0.0000
OH	0.1038	0.0001	0.0000	0.0000
CONDENSED PHASES	0	0	0	0
C/SOLID/	0	0	0	0

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3366.0	1745.4	1211.5	799.14
-14.773	-100.35	-123.42	-141.14
254.39	254.39	254.39	254.39
44.367	41.379	39.589	36.314
4.0980	3.9849	3.9847	3.9843
0.0598	0.0003	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0104	0.0000	0.0000	0.0000
0.3225	0.4298	0.6125	0.9206
1.1682	1.1366	0.9560	0.6475
1.0710	0.8850	0.7023	0.3934
0.4975	0.6836	0.8662	1.1749
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0002
0.0150	0.0000	0.0000	0.0000
0.0959	0.0000	0.0000	0.0000
0.8376	0.8477	0.8477	0.8477
0.0202	0.0000	0.0000	0.0000
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
C
N
O
H₂
H₂O
CO
CO₂
CH
CH₂
CH₄
O₂
OH
N₂
NO
CONDENSED PHASES
C/SOLID/

TABLE 71

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	NF3	80.000		1.532	144.00
	CH2	20.000		0.9200	298.16
INGREDIENT DATA:	NF3		HEAT OF FORM.		
	CH2		-32.000		
			-6.5000		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	2.6518			
	C	1.4259			
	N	1.1266			
	F	3.5799			
PROPELLANT ENTHALPY		-45.321	KCAL/100 GM		
PROPELLANT DENSITY		1.352	CM/CC		
	CHAMBER	1000.0	EXHAUST		
			14.70		
PRESSURE (PSI)				0.0498	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	0.2000
ISP (SEC)			283.54	323.38	351.43
IVSP(LB-SEC/CU IN)			13.851	15.798	17.168
TEMPERATURE (K)			2294.6	1656.6	1058.8
CP (CAL/GM-DEG.K)			0.40182	0.34228	0.35212
MOL. WT.-EFFECTIVE			29.015	28.197	28.191
CP/CV -EFFECTIVE			1.2144	1.2261	1.2503
CF -APPROX.			1.6650	1.0939	2.0636
PEAF/M (SEC)			24.975	15.714	9.2401
AE/AT -APPROX.			9.9792	46.138	271.29
FROZEN EQUILIBRIA					
ISP (SEC)			268.89	305.78	328.69
TEMPERATURE (K)			1684.7	1021.1	520.68
C* (FT/SEC)			3725.8		
			5479.1		
CF			1.5790	1.7956	1.9301
PEAF/M (SEC)			20.728	11.048	5.2408
AE/AT			8.2825	32.437	153.87

TABLE 72

CASE					BASIS: 100 GM PROPELLANT				
PRESSURE (PSI)					CHAMBER				
TEMPERATURE (KELVIN)					EXHAUST				
ENTHALPY (KILOCALORIES)					EXHAUST				
ENTROPY (CALORIES/DEG.K)					EXHAUST				
HEAT CAPACITY (CAL/K)					EXHAUST				
MOLES OF GAS					EXHAUST				
MOLECULAR COMPOSITION:					EXHAUST				
H					EXHAUST				
C					EXHAUST				
N					EXHAUST				
F					EXHAUST				
H2					EXHAUST				
HF					EXHAUST				
N2					EXHAUST				
F2					EXHAUST				
CH					EXHAUST				
CH2					EXHAUST				
CH4					EXHAUST				
CF					EXHAUST				
CF2					EXHAUST				
CF3					EXHAUST				
CF4					EXHAUST				
CN					EXHAUST				
C2N2					EXHAUST				
C2H2					EXHAUST				
CHF3					EXHAUST				
CH2F2					EXHAUST				
HCN					EXHAUST				
NH					EXHAUST				
NH2					EXHAUST				
NH3					EXHAUST				
CONDENSED PHASES					EXHAUST				
C/SOLID/					EXHAUST				
					1.2194	1.2908	1.2935	1.2939	

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CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLF3	79.000		1.810	298.16
	CH2	21.000		0.9200	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	CLF3		-44.400		
	CH2		-6.5000		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	2.9944			
	C	1.4972			
	F	2.5634			
	CL	0.6544			
	PROPELLANT ENTHALPY	-47.670	KCAL/100 GM		
	PROPELLANT DENSITY	1.504	GM/CC		
	CHAMBER	14.70	EXHAUST		
	1000.0				
	PRESSURE (PSI)			0.0544	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	0.2000
	ISP (SEC)	251.83		285.78	311.05
	IVP(LB-SEC/CU IN)	13.688		15.533	16.907
	TEMPERATURE (K)	1873.8		1435.4	994.01
	CP (CAL/GM-DEG.K)	0.35359		0.33597	0.31531
	MOL. WT.-EFFECTIVE	30.649		31.619	32.187
	CP/CV -EFFECTIVE	1.2138		1.2301	1.2435
	CF -APPROX.	1.6125		1.8299	1.9917
	PEAF/M (SEC)	20.990		13.734	8.5837
	AE/AT -APPROX.	9.1454		43.971	274.82
	FROZEN EQUILIBRIA				
	ISP (SEC)	246.90		274.61	299.95
	TEMPERATURE (K)	1596.8		1015.0	571.32
	C* (FT/SEC)	5024.7			
	CF				
	PEAE/M (SEC)	1.5809		1.7904	1.9206
	AE/AT	19.138		10.742	5.6363
		8.3385		34.391	180.45

TABLE 74

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3495.2	1873.8	1435.4	994.01
ENTHALPY (KILOCALOR/ES)	-47.670	-120.56	-141.53	-158.87
ENTROPY (CALORIES/DEG.K)	200.91	200.91	200.91	200.91
HEAT CAPACITY (CAL/K)	38.610	35.359	33.597	31.531
MOLES OF GAS	3.4226	3.2627	3.1626	3.1068
MOLECULAR COMPOSITION:				
H	0.0119	0.0000	0.0000	0.0000
C	0.0002	0.0000	0.0000	0.0000
F	0.0476	0.0003	0.0000	0.0000
CL	0.3748	0.1648	0.0335	0.0006
H2	0.0082	0.0000	0.0000	0.0000
HCL	0.4588	0.5366	0.5723	0.6294
HF	2.5040	2.4578	2.3221	2.1650
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0096	0.0764	0.0743	0.0122
CLF	0.0016	0.0002	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0001	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CF	0.0006	0.0000	0.0000	0.0000
CF2	0.0018	0.0000	0.0000	0.0000
CF3	0.0018	0.0012	0.0001	0.0000
CF4	0.0002	0.0253	0.0602	0.0996
C2H2	0.0015	0.0000	0.0000	0.0000
CHF3	0.0000	0.0000	0.0000	0.0000
CH2F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	1.4896	1.4706	1.4369	1.3976

TABLE 75

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CH ₂	20.000		0.9200	298.16
	CLO ₃ F	80.000		1.430	298.16
	INGREDIENT DATA:		HEAT OF FORM.		
	CH ₂		-6.5000		
	CLO ₃ F		-10.100		
	ATOMIC COMPOSITION (GM AT/100GM)				
	H	2.8518			
	C	1.4259			
	O	2.3424			
	F	0.7808			
	CL	0.7808			
	PROPELLANT ENTHALPY	-17.155	KCAL/100 GM		
	PROPELLANT DENSITY	1.287	GM/CC		
	CHAMBER	1000.0			
	EXHAUST	14.70			
	PRESSURE (PSI)			0.0465	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	0.2000
	ISP (SEC)			312.11	339.17
	IVSP (LB-SEC/CU IN)			14.656	15.774
	TEMPERATURE (K)			1365.9	850.48
	CP (CAL/GM-DEG.K)	3694.0		0.33120	0.30752
	MOL. WT.-EFFECTIVE	0.37426		27.528	27.528
	CP/CV -EFFECTIVE	25.801		1.2787	1.3068
	CF -APPROX.	1.2591		1.8686	2.0113
	PEAF/M (SEC)			13.614	7.8753
	AE/AT -APPROX.			40.366	233.50
	FROZEN EQUILIBRIA				
	ISP (SEC)			296.97	315.81
	TEMPERATURE (K)			808.50	349.15
	C* (FT/SEC)	3694.0			
	CF (SEC)	5425.6			
	PEAF/M (SEC)			1.7611	1.8728
	AE/AT			9.1228	3.7047
				27.049	109.84

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	3694.0	2043.9	1365.9	850.48
ENTROPY (CALORIES/DEG.K)	-17.155	-106.99	-131.27	-149.36
HEAT CAPACITY (CAL/K)	233.31	233.31	233.31	233.31
MOLES OF GAS	37.426	35.198	33.120	30.752
MOLECULAR COMPOSITION:	3.8758	3.6359	3.6327	3.6326
H	0.0952	0.0018	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
O	0.0295	0.0000	0.0000	0.0000
F	0.0063	0.0000	0.0000	0.0000
CL	0.1659	0.0041	0.0000	0.0000
H2	0.2001	0.1988	0.2915	0.4743
H2O	0.4301	0.4472	0.3536	0.1706
HCL	0.6126	0.7767	0.7608	0.7808
HF	0.7745	0.7808	0.7808	0.7808
CO	1.1289	0.9571	0.8630	0.6801
CO2	0.2970	0.4688	0.5629	0.7458
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0252	0.0000	0.0000	0.0000
OH	0.1092	0.0005	0.0000	0.0000
CLO	0.0003	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0010	0.0000	0.0000	0.0000
CONDENSED PHASES	0	0	0	0
C/SOLID/				

TABLE 77

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	NO ₂ ClO ₄	79.000		2.220	298.16
	CH ₂	21.000		0.9200	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	NO ₂ ClO ₄	8.0000			
	CH ₂	-6.5000			
ATOMIC COMPOSITION (GM AT/100GM)					
H		2.9944			
C		1.4972			
N		0.5431			
O		3.2585			
CL		0.5431			
PROPELLANT ENTHALPY		KCAL/100 GM			
		-5.3872			
PROPELLANT DENSITY		CM/CC			
		1.712			
				0.0618 LB/CU IN	
CHAMBER	EXHAUST	EXHAUST	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	2.000	0.2000	0.2000
	276.24	316.56	316.56	343.46	343.46
	17.210	19.580	19.580	21.244	21.244
	2205.3	1553.3	1553.3	1017.9	1017.9
	0.36720	0.36880	0.36880	0.34167	0.34167
	28.203	28.268	28.268	28.268	28.268
	1.2225	1.2355	1.2355	1.2590	1.2590
	1.6751	1.9057	1.9057	2.0677	2.0677
	24.296	15.008	15.008	9.0640	9.0640
	9.9530	45.175	45.175	272.84	272.84
	261.50	296.87	296.87	318.32	318.32
	1575.3	926.63	926.63	438.70	438.70
	1.5743	1.7872	1.7872	1.9164	1.9164
	19.834	10.277	10.277	4.5376	4.5376
	8.1251	30.935	30.935	136.59	136.59

TABLE 78

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3586.8	2205.3	1553.3	1017.9
TEMPERATURE (KELVIN)	-5.3872	-94.362	-120.55	-140.96
ENTHALPY (KILOCALORIES)	239.44	239.44	239.44	239.44
ENTROPY (CALORIES/DEG.K)	40.524	38.720	36.880	34.167
HEAT CAPACITY (CAL/K)	3.8083	3.5457	3.5376	3.5375
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0806	0.0049	0.0001	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0336	0.0000	0.0000	0.0000
CL	0.0906	0.0074	0.0001	0.0000
H2	0.2286	0.2030	0.2828	0.4771
H2O	0.9192	1.0221	0.9429	0.7486
HCL	0.4515	0.5357	0.5430	0.5431
CO	0.9918	0.7621	0.6798	0.4845
CO2	0.5054	0.7351	0.5184	1.0127
O2	0.0550	0.0001	0.0000	0.0000
OH	0.1667	0.0035	0.0000	0.0000
N2	0.2584	0.2714	0.2715	0.2715
NO	0.0251	0.0002	0.0000	0.0000
CL4	0.0004	0.0000	0.0000	0.0000
CLO	0.0002	0.0000	0.0000	0.0000
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
C2H2	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 79

CASE	PROPELLANT COMPOSITION	WEIGHTS	HEAT OF FORM.	DENSITY	REF. TEMP.
	NH ₄ ClO ₄	91.500	-69.420	1.960	298.16
	CH ₂	8.5000	-6.5000	0.9200	298.16
INGREDIENT DATA:	FORMULA				
	NH ₄ ClO ₄				
	CH ₂				
ATOMIC COMPOSITION(GM AT/100GM)					
H		4.3270			
C		0.6060			
N		0.7787			
O		3.1150			
CL		0.7787			
PROPELLANT ENTHALPY		-57.999	KCAL/100 GM		
PROPELLANT DENSITY		1.788	GM/CC		
PRESSURE (PSI)		1000.0	EXHAUST	0.0646	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	0.2000
ISP (SEC)				281.91	304.38
IVSP(LB-SEC/CU IN)				18.213	19.665
TEMPERATURE (K)				1149.1	714.96
CP (CAL/GM-DEG.K)		2975.4		0.35924	0.32157
MOL. WT.-EFFECTIVE		0.42873		27.688	27.772
CP/CV -EFFECTIVE		26.733		1.2497	1.2862
CF -APPROX.		1.2098		1.8692	2.0182
PEAE/M (SEC)				12.728	7.3123
AE/AT -APPROX.				42.197	242.42
FROZEN EQUILIBRIA					
ISP (SEC)				272.34	292.28
TEMPERATURE (K)		2975.4		836.12	426.81
C* (FT/SEC)		4852.4			
CF					
PEAE/M (SEC)				1.8058	1.9380
AE/AT				9.9289	4.7226
				32.917	156.57

TABLE 80

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	2975.4	1662.1	1149.1	714.96
TEMPERATURE (KELVIN)	-57.999	-129.12	-149.34	-164.47
ENTHALPY (KILOCALORIES)	232.57	232.57	232.57	232.57
ENTROPY (CALORIES/DEG.K)	42.873	39.334	35.924	32.157
HEAT CAPACITY (CAL/K)	3.7406	3.6143	3.6117	3.6007
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0079	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0075	0.0000	0.0000	0.0000
CL	0.0601	0.0062	0.0007	0.0000
H2	0.0537	0.0002	0.0000	0.0000
H2O	1.7054	1.7772	1.7767	1.7981
HCL	0.7163	0.7709	0.7735	0.7308
CO	0.1116	0.0002	0.0000	0.0000
CO2	0.4944	0.6058	0.6060	0.6060
CH	0.0000	0.0000	0.0000	0.0000
CH2	0.0000	0.0000	0.0000	0.0000
CH4	0.0000	0.0000	0.0000	0.0000
O2	0.0972	0.0618	0.0631	0.0524
OH	0.0845	0.0012	0.0000	0.0000
N2	0.3780	0.3889	0.3893	0.3894
NO	0.0226	0.0010	0.0000	0.0000
CL0	0.0001	0.0000	0.0000	0.0000
CL2	0.0011	0.0008	0.0023	0.0240
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 81

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	C4N2	55.000		0.9700	298.16
	O2	45.000		1.142	90.200
INGREDIENT DATA:	C4N2	HEAT OF FORM.			
	O2	118.00			
		-3.0500			
ATOMIC COMPOSITION(GM AT/100GM)					
C		2.8926			
N		1.4463			
O		2.8125			
PROPELLANT ENTHALPY		81.001	KCAL/100 GM		
PROPELLANT DENSITY		1.040	GM/CC		
	CHAMBER	14.70	EXHAUST		
		1000.0			
PRESSURE (PSI)				0.0376	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)				331.23	353.41
TEMPERATURE (K)				12.452	13.286
CP (CAL/GM-DEG.K)				1374.4	914.42
MOL. WT.-EFFECTIVE				0.30285	0.28210
CP/CV -EFFECTIVE				28.289	29.160
CF -APPROX.				1.3020	1.3185
PEAE/M (SEC)				1.7590	1.8768
AE/AT -APPROX.				12.682	7.6715
FROZEN EQUILIBRIA				33.674	203.70
ISP (SEC)				326.48	346.06
TEMPERATURE (K)				1166.2	620.01
C* (FT/SEC)					
CF					
PEAE/M (SEC)				1.7338	1.8378
AE/AT				11.070	5.5526
				29.394	147.44

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
5036.3	2163.2	1374.4	914.42
81.001	-20.694	-45.091	-62.543
224.16	224.16	224.16	224.16
32.640	31.317	30.285	28.210
3.5846	3.5357	3.5349	3.4294
0.0098	0.0000	0.0000	0.0000
0.0068	0.0000	0.0000	0.0000
0.0020	0.0000	0.0000	0.0000
2.8089	2.8124	2.8111	2.5999
0.0006	0.0000	0.0007	0.1063
0.0731	0.0001	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.6828	0.7231	0.7232	0.7232
0.0005	0.0000	0.0000	0.0000
0	0.0800	0.0808	0.1864

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

C
N
O
CO
CO2
CN
C2N2
O2
N2
NO

CONDENSED PHASES
C/SOLID/

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	C4N2	18.000		0.9700	298.16
	F2	82.000		1.510	85.200
INGREDIENT DATA:	C4N2		HEAT OF FORM.		
	F2		118.00		
			-3.4670		
ATOMIC COMPOSITION (GM AT/100GM)					
	C	0.9467			
	N	0.4733			
	F	4.3158			
PROPELLANT ENTHALPY		20.445	KCAL/100 GM		
PROPELLANT DENSITY		1.372	GM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)				0.0496	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
	ISP (SEC)			2.000	0.2000
	IVSP (LB-SEC/CU IN)			291.10	325.30
	TEMPERATURE (K)			14.435	16.131
	CP (CAL/GM-DEG.K)			2655.1	2354.2
	MOL. WT.-EFFECTIVE			0.29201	0.29173
	CP/CV -EFFECTIVE			45.760	48.684
	CF -APPROX.			1.1747	1.1627
	PEAE/M (SEC)			1.9683	2.1996
	AE/AT -APPROX.			17.233	12.852
				58.261	434.50
FROZEN EQUILIBRIA					
	ISP (SEC)			267.17	286.22
	TEMPERATURE (K)			1179.8	728.07
	C* (FT/SEC)				
	CF				
	PEAE/M (SEC)			1.8065	1.9353
	AE/AT			10.195	5.8726
				34.467	193.54

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4037.6	2983.3	2655.1	2354.2
20.445	-51.844	-76.940	-101.17
177.88	177.88	177.88	177.88
29.182	29.210	29.201	29.173
2.6703	2.3172	2.1853	2.0541
0.0007	0.0000	0.0000	0.0000
0.0002	0.0000	0.0000	0.0000
1.4970	1.1369	1.0035	0.8713
0.0134	0.0016	0.0005	0.0001
0.1408	0.0476	0.0252	0.0109
0.5527	0.4828	0.4103	0.3152
0.2155	0.4084	0.5076	0.6192
0.0231	0.0062	0.0030	0.0012
0.0002	0.0000	0.0000	0.0000
0.2248	0.2335	0.2351	0.2361
0.0019	0.0001	0.0000	0.0000
0	0	0	0

PRESSURE (PSI)
 TEMPERATURE (KELVIN)
 ENTHALPY (KILOCALORIES)
 ENTROPY (CALORIES/DEG.K)
 HEAT CAPACITY (CAL/K)
 MOLES OF GAS
 MOLECULAR COMPOSITION:

C
 N
 F
 CF
 CF2
 CF3
 CF4
 CN
 C2N2
 N2
 F2

CONDENSED PHASES
 C/SOLID/

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	C4N2	32.000		0.9700	298.16
	OF2	68.000		1.530	128.00
	C4N2		HEAT OF FORM.		
	OF2		118.00		
			3.6000		
	ATOMIC COMPOSITION(GM AT/100GM)				
	C	1.6830			
	N	0.6415			
	O	1.2592			
	F	2.5185			
	PROPELLANT ENTHALPY	54.181	KCAL/100 GM		
	PROPELLANT DENSITY	1.291	CM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
	PRESSURE (PSI)			0.0466	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	EXHAUST
	ISP (SEC)			2.000	0.2000
	IVSP(LB-SEC/CU IN)			318.92	353.11
	TEMPERATURE (K)			14.880	16.476
	CP (CAL/GM-DEG.K)	3991.6		2292.8	1967.9
	MOL. WT.-EFFECTIVE	0.30162		0.29938	0.29770
	CP/CV -EFFECTIVE	29.296		35.471	38.110
	CF -APPROX.	1.2902		1.2302	1.2124
	PEAF/M (SEC)			1.9554	2.1651
	AE/AT -APPROX.			17.523	12.643
	FROZEN EQUILIBRIA			53.721	387.59
	ISP (SEC)			284.33	300.65
	TEMPERATURE (K)	3991.6		846.35	423.50
	C* (FT/SEC)	5247.4			
	CF			1.7433	1.8434
	PEAE/M (SEC)			8.7847	4.1572
	AE/AT			26.931	127.45

TABLE 86

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3991.6	2708.4	2292.8	1967.9
TEMPERATURE (KELVIN)	54.181	-34.042	-62.711	-89.118
ENTHALPY (KILOCALORIES)	205.98	205.88	205.88	205.88
ENTROPY (CALORIES/DEG.K)	30.162	30.087	29.938	29.770
HEAT CAPACITY (CAL/K)	3.4135	2.9837	2.8192	2.6240
MOLES OF GAS				
MOLECULAR COMPOSITION:				
C	0.0006	0.0000	0.0000	0.0000
N	0.0002	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
F	1.3211	0.8799	0.7154	0.5202
CO	1.2514	1.2414	1.1953	1.1059
CO2	0.0000	0.0001	0.0013	0.0090
O2	0.0000	0.0000	0.0000	0.0000
N2	0.4082	0.4207	0.4207	0.4207
NO	0.0000	0.0000	0.0000	0.0000
F2	0.0011	0.0001	0.0000	0.0000
CF	0.0086	0.0000	0.0000	0.0000
CF2	0.0744	0.0018	0.0000	0.0000
CF3	0.2393	0.0884	0.0177	0.0033
CF4	0.0761	0.3336	0.4073	0.4294
CN	0.0243	0.0000	0.0000	0.0000
C2N2	0.0002	0.0000	0.0000	0.0000
COF2	0.0077	0.0177	0.0603	0.1354
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 87

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	C4N2	25.000		0.9700	298.16
	H2O2	75.000		1.443	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
C4N2	C4N2	118.00			
H2O2	H2O2	-44.840			
ATOMIC COMPOSITION (GM AT/100GM)					
H	4.4097				
C	1.3148				
N	0.6574				
O	4.4097				
PROPELLANT ENTHALPY		KCAL/100 GM			
PROPELLANT DENSITY		GM/CC			
	-60.078				
CHAMBER					
	1.286				
CHAMBER					
	1000.0				
EXHAUST					
	14.70				
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)					
IVSP (LB-SEC/CU IN)					
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAF/M (SEC)					
AE/AT					

TABLE 88

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3319.9	2093.1	1509.7	1013.3
TEMPERATURE (KELVIN)	-60.078	-149.97	-177.28	-199.54
ENTHALPY (KILOCALORIES)	262.21	262.21	262.21	262.21
ENTROPY (CALORIES/DEG.K)	49.055	46.524	43.933	40.086
HEAT CAPACITY (CAL/K)	4.0868	3.8519	3.8484	3.8484
MOLES OF GAS	0.0395	0.0021	0.0070	0.0000
MOLECULAR COMPOSITION:	0.0000	0.0000	0.0000	0.0000
H	0.0000	0.0000	0.0000	0.0000
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0239	0.0000	0.0000	0.0000
H2	0.1776	0.1278	0.1844	0.2919
H2O	1.9158	2.0739	2.0204	1.9129
CO	0.5492	0.2987	0.2403	0.1329
CO2	0.7656	1.0161	1.0745	1.1819
CN	0.0000	0.0000	0.0000	0.0000
HCN	0.0000	0.0000	0.0000	0.0000
O2	0.1031	0.0003	0.0000	0.0000
OH	0.1833	0.0041	0.0000	0.0000
N2	0.3287	0.3287	0.3287	0.3287
CONDENSED PHASES	0	0	0	0
C/SOLID/	0	0	0	0

TABLE 90

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.0000	0.2000
4126.9	2640.5	1875.2	1179.4
52.098	-38.124	-65.592	-86.594
214.78	214.78	214.78	214.78
32.559	32.364	31.648	29.467
3.3917	3.0829	3.0622	3.0622
0.0000	0.0000	0.0000	0.0000
0.0006	0.0000	0.0000	0.0000
0.1466	0.0052	0.0000	0.0000
1.5162	1.0408	1.0046	1.0046
0.3771	0.8526	0.3887	0.3888
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.1228	0.0112	0.0000	0.0000
1.1088	1.1646	1.1688	1.1689
0.1195	0.0085	0.0000	0.0000
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

C
N
O
CO
CO2
CN
C2N2
O2
N2
NC

CONDENSED PHASES
C/SOLID/

589

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	REF. TEMP.
C4N2		15.000		298.16
NF3		85.000		144.00
INGREDIENT DATA:	FORMULA	HEAT OF FORM.	DENSITY	
C4N2	C4N2	118.00	0.9700	
NF3	NF3	-32.000	1.532	
ATOMIC COMPOSITION(GM AT/100GM)				
C		0.7889		
N		1.5915		
F		3.5911		
PROPELLANT ENTHALPY		-15.033	KCAL/100 GM	
PROPELLANT DENSITY		1.410	GM/CC	
	CHAMBER	14.70	EXHAUST	
		1000.0		
PRESSURE (PSI)				
SHIFTING EQUILIBRIA				
ISP (SEC)				
IVSP(LB-SEC/CU IN)				
TEMPERATURE (K)				
CP (CAL/GM-DEG.K)				
MOL. WT.-EFFECTIVE				
CP/CV -EFFECTIVE				
CF -APPROX.				
PEAF/M (SEC)				
AE/AT -APPROX.				
FROZEN EQUILIBRIA				
ISP (SEC)				
TEMPERATURE (K)				
C# (FT/SEC)				
CF				
PEAF/M (SEC)				
AE/AT				

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
GASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3679.5	2706.5	2373.8	1969.2
TEMPERATURE (KELVIN)	-15.033	-76.748	-98.339	-118.88
ENTHALPY (KILOCALORIES)	171.54	171.54	171.54	171.54
ENTROPY (CALORIES/DEG.K)	29.957	29.837	29.746	29.538
HEAT CAPACITY (CAL/K)	2.4757	2.1978	2.0984	2.0259
MOLES OF GAS				
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0001	0.0000	0.0000	0.0000
F	0.8918	0.6132	0.5138	0.4412
CF	0.0011	0.0000	0.0000	0.0000
CF2	0.0344	0.0036	0.0006	0.0000
CF3	0.3705	0.1697	0.0770	0.0056
CF4	0.3789	0.6154	0.7112	0.7832
CN	0.0039	0.0002	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
N2	0.7937	0.7956	0.7957	0.7957
F2	0.0012	0.0001	0.0000	0.0000
CONDENSED PHASES				
C/SOLID/	0	0	0	0

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

C

N

F

CL

CF

CF2

CF3

CF4

CN

C2N2

N2

F2

CL2

CLF

CONDENSED PHASES

C/SOLID/

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3403.8	2432.3	2060.5	1695.7
-21.610	-68.845	-85.117	-100.07
141.62	141.62	141.62	141.62
24.534	24.489	24.352	24.042
2.0422	1.8632	1.7925	1.7025
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.3264	0.1320	0.0830	0.0631
0.7360	0.7971	0.7549	0.6033
0.0003	0.0000	0.0000	0.0000
0.0139	0.0004	0.0000	0.0000
0.2526	0.0580	0.0087	0.0002
0.4162	0.6253	0.6750	0.6835
0.0007	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.1706	0.1709	0.1709	0.1709
0.0003	0.0000	0.0000	0.0000
0.0799	0.0645	0.0862	0.1562
0.0452	0.0148	0.0138	0.0252
0	0	0	0

593

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	C4N2	35.000		0.9700	298.16
	CLO3F	65.000		1.430	298.16
INGREDIENT DATA:	C4N2		HEAT OF FORM.		
	CLO3F		118.00		
			-10.100		
ATOMIC COMPOSITION(GM AT/100GM)					
C	1.8407				
N	0.9204				
O	1.9032				
F	0.6344				
CL	0.6344				
PROPELLANT ENTHALPY	47.894	KCAL/100 GM			
PROPELLANT DENSITY	1.226	GM/CC			
	CHAMBER		EXHAUST		
	1000.0		14.70		
PRESSURE (PSI)				0.0443	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)					315.12
TEMPERATURE (K)					13.963
CP (CAL/GM-DEG.K)					1343.0
MOL. WT.-EFFECTIVE					0.26029
CP/CV -EFFECTIVE					37.561
CF -APPROX.					1.2551
PEAE/M (SEC)					2.1099
AE/AT -APPROX.					9.8098
					328.41
FROZEN EQUILIBRIA					267.68
ISP (SEC)					298.16
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAF/M (SEC)					
AE/AT					

TABLE 96

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3423.8	2187.8	1756.9	1343.0
ENTHALPY (KILOCALORIES)	47.894	-24.654	-46.983	-66.230
ENTROPY (CALORIES/DEG.K)	194.42	194.42	194.42	194.42
HEAT CAPACITY (CAL/K)	27.373	27.039	26.690	26.029
MOLES OF GAS	3.4067	2.9347	2.7894	2.6623
MOLECULAR COMPOSITION:				
C	0.0000	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0010	0.0000	0.0000	0.0000
F	0.4960	0.0657	0.0043	0.0000
CL	0.5538	0.4890	0.3310	0.0802
CO	1.7236	1.4998	1.4646	1.4611
CO2	0.0661	0.1113	0.1313	0.1536
N2	0.4602	0.4602	0.4602	0.4602
CL2	0.0256	0.0664	0.1502	0.2731
CLF	0.0293	0.0127	0.0030	0.0001
CF	0.0000	0.0000	0.0000	0.0000
CF2	0.0001	0.0000	0.0000	0.0000
CF3	0.0019	0.0009	0.0002	0.0000
CF4	0.0026	0.0078	0.0686	0.0911
COF2	0.0464	0.1809	0.1760	0.1348
CONDENSED PHASES				
C/SOLID/	0	0	0	0

TABLE 97

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	NO ₂ ClO ₄	61.000		2.220	298.16
	C ₄ N ₂	39.000		0.9700	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	NO ₂ ClO ₄		8.0000		
	C ₄ N ₂		118.00		
ATOMIC COMPOSITION (GM AT/100GM)					
	C	2.0511			
	N	1.4449			
	O	2.5161			
	CL	0.4193			
PROPELLANT ENTHALPY		63.863	KCAL/100 GM		
PROPELLANT DENSITY		1.477	CM/CC		
	CHAMBER		EXHAUST		
		1000.0	14.70	0.0534	LB/CU IN
				EXHAUST	0.2000
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)					
IVSP (LB-SEC/CU IN)					
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAF/M (SEC)					
AE/AT					

TABLE 98

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4272.3	2207.6	1621.9	1095.5
TEMPERATURE (KELVIN)	63.863	-23.821	-47.139	-65.887
ENTHALPY (KILOCALORIES)	206.55	206.55	206.55	206.55
ENTROPY (CALORIES/DEG.K)	29.825	29.075	28.392	26.600
HEAT CAPACITY (CAL/K)	3.3743	3.1636	3.0605	2.9881
MOLES OF GAS	0.0000	0.0000	0.0000	0.0000
MOLECULAR COMPOSITION:	0.0008	0.0000	0.0000	0.0000
C	0.1108	0.0000	0.0000	0.0000
N	0.4129	0.3606	0.1545	0.3098
O	1.6438	1.5863	1.5862	1.5862
CL	0.2073	0.4648	0.4649	0.4649
CO	0.0422	0.0000	0.0000	0.0000
CO2	0.6918	0.7224	0.7224	0.7224
O2	0.0604	0.0001	0.0000	0.0000
N2	0.0022	0.0294	0.1324	0.2048
NO	0.0020	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CN	0.0000	0.0000	0.0000	0.0000
C2N2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES	0	0	0	0
C/SOLID/				

TABLE 99

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	C4N2	17.000		0.9700	298.16
	NH4CLO4	83.000		1.960	298.16
INGREDIENT DATA:	FORMULA	H*AT OF FORM.			
	C4N2	118.00			
	NH4CLO4	-69.420			
ATOMIC COMPOSITION (GM AT/100GM)					
	H	2.8256			
	C	0.8941			
	N	1.1534			
	O	2.8256			
	CL	0.7064			
PROPELLANT ENTHALPY		-22.663	KCAL/100 GM		
PROPELLANT DENSITY		1.670	GM/CC		
	CHAMBER	14.70	EXHAUST	0.0603	LB/CU IN
		1000.0		2.000	EXHAUST
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
	ISP (SEC)				
	IVSP (LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)				
	MOL. WT.-EFFECTIVE				
	CP/CV -EFFECTIVE				
	CF -APPROX.				
	PEAE/M (SEC)				
	AE/AT -APPROX.				
FROZEN EQUILIBRIA					
	ISP (SEC)				
	TEMPERATURE (K)				
	C* (FT/SEC)				
	CF				
	PEAE/M (SEC)				
	AE/AT				

TABLE 100

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3263.6	2096.2	1532.0	986.87
-22.663	-97.895	-121.26	-139.79
221.40	221.40	221.40	221.40
38.362	36.814	35.114	31.682
3.4975	3.2609	3.2371	3.2368
0.0199	0.0006	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0190	0.0002	0.0000	0.0000
0.0981	0.0200	0.0006	0.0000
0.0702	0.0115	0.0072	0.0142
0.9714	1.0544	1.0527	1.0454
0.6083	0.6864	0.7058	0.7064
0.3184	0.0444	0.0153	0.0079
0.5757	0.8496	0.8788	0.8861
0.1058	0.0094	0.0000	0.0000
0.1142	0.0066	0.0000	0.0000
0.5570	0.5758	0.5767	0.5767
0.0395	0.0019	0.0000	0.0000
0	0	0	0

PRESSURE (PSI)

TEMPERATURE (KELVIN)

ENTHALPY (KILOCALORIES)

ENTROPY (CALORIES/DEG.K)

HEAT CAPACITY (CAL/K)

MOLES OF GAS

MOLECULAR COMPOSITION:

H

C

N

O

CL

H2

H2O

HCL

CO

CO2

O2

OH

N2

NO

CONDENSED PHASES

C/SOLID/

TABLE 102

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3771.8	2498.2	2030.2	1816.4
TEMPERATURE (KELVIN)	-1.3116	-116.16	-153.77	-189.22
ENTHALPY (KILOCALORIES)	296.86	296.86	296.86	296.86
ENTROPY (CALORIES/DEG.K)	59.724	57.859	56.741	57.307
HEAT CAPACITY (CAL/K)	4.5782	4.2667	4.1636	3.9179
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.3917	0.0784	0.0169	0.0109
B	0.0170	0.0003	0.0000	0.0000
O	0.0002	0.0000	0.0000	0.0000
H2	2.1007	2.3270	2.3688	2.4528
H2O	0.0198	0.0024	0.0007	0.0002
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0021	0.0000	0.0000	0.0000
BO	0.3237	0.0334	0.0039	0.0015
B2O2	0.8575	0.9601	0.8067	0.6449
B2O3	0.0865	0.1886	0.3135	0.3107
HB02	0.7772	0.6765	0.6576	0.4968
H3B03	0.0000	0.0000	0.0000	0.0000
H3B3O6	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0016	0.0000	0.0000	0.0000
CONDENSED PHASES				
B2O3/L/	0	0	0	0.2192
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0.1049	0.1596

TABLE 103

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	F2	80.000		1.510	85.200
	B5H9	20.000		0.6230	298.16
INGREDIENT DATA:	F2		HEAT OF FORM.		
	B5H9		-3.4670		
			7.7400		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	2.8494			
	B	1.5830			
	F	4.2105			
PROPELLANT ENTHALPY			KCAL/100 GM		
PROPELLANT DENSITY			GM/CC		
			1.175		
			CHAMBER		
			1000.0		
PRESSURE (PSI)				0.0425	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
				2.000	0.2000
ISP (SEC)				408.94	449.41
IVSP(LB-SEC/CU IN)				17.365	19.084
TEMPERATURE (K)				2532.4	2102.5
CP (CAL/GM-DEG.K)				0.38494	0.38263
MOL. WT.-EFFECTIVE				25.584	27.270
CP/CV -EFFECTIVE				1.2528	1.2353
CF -APPROX.				1.9172	2.1069
PEAE/M (SEC)				20.927	14.832
AE/AT -APPROX.				49.054	347.68
FROZEN EQUILIBRIA					
ISP (SEC)				368.22	388.38
TEMPERATURE (K)				977.05	460.08
C* (FT/SEC)					
CF (SEC)					
PEAE/M (SEC)					
AE/AT					
				1.7262	1.8208
				10.764	4.8057
				25.232	112.65

TABLE 104

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4991.0	3105.2	2532.4	2102.5
TEMPERATURE (KELVIN)	-4.8485	-152.40	-197.04	-236.96
ENTHALPY (KILOCALORIES)	270.61	270.61	270.61	270.61
ENTROPY (CALORIES/DEG.K)	40.507	38.897	38.494	38.263
HEAT CAPACITY (CAL/K)	4.6922	4.1331	3.9086	3.6671
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.6675	0.2436	0.1120	0.0453
B	0.0022	0.0000	0.0000	0.0000
F	0.4208	0.0114	0.0008	0.0000
H2	0.1610	0.3107	0.5245	0.7653
HF	1.8599	1.9844	1.6883	1.2734
F2	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
BF	1.3274	1.1748	1.0144	0.8064
BF2	0.1577	0.1846	0.1987	0.1990
BF3	0.0956	0.2236	0.3698	0.5776
CONDENSED PHASES				
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 105

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	OF2	81.500		1.530	128.00
	B5H9	18.500		0.6230	298.16
INGREDIENT DATA:	OF2		HEAT OF FORM.		
	B5H9		3.6000		
ATOMIC COMPOSITION(GM AT/100GM)			7.7400		
	H	2.6357			
	B	1.4642			
	O	1.5092			
	F	3.0185			
PROPELLANT ENTHALPY		7.7000	KCAL./100 GM		
PROPELLANT DENSITY		1.205	GM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)				0.0435	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)				421.50	465.58
TEMPERATURE (K)				18.356	20.276
CP (CAL/GM-DEG.K)				2970.2	2339.1
MOL. WT.-EFFECTIVE				0.40194	0.39248
CP/CV -EFFECTIVE				26.395	27.604
CF -APPROX.				1.2305	1.2246
PEAE/M (SEC)				1.9577	2.1624
AE/AT -APPROX.				23.082	15.736
				53.604	365.43
FROZEN EQUILIBRIA					
ISP (SEC)				376.16	399.81
TEMPERATURE (K)				1190.0	609.23
C* (FT/SEC)				1.7471	1.8569
CF				12.335	5.9411
PEAE/M (SEC)				28.645	137.97
AE/AT					

TABLE 106

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	5215.3	3567.0	2970.2	2339.1
TEMPERATURE (KELVIN)	7.7000	-146.25	-196.48	-241.42
ENTHALPY (KILOCALORIES)	273.76	273.76	273.76	273.76
ENTHALPY (CALORIES/DEG.K)	41.812	40.810	40.194	39.248
HEAT CAPACITY (CAL/K)	4.5096	3.9783	3.7886	3.6227
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.6985	0.6263	0.4094	0.1260
B	0.0015	0.0000	0.0000	0.0000
O	0.2543	0.0564	0.0120	0.0003
F	0.3643	0.0644	0.0126	0.0006
H2	0.1875	0.2116	0.2924	0.4298
H2O	0.0222	0.0229	0.0311	0.0355
HF	1.2067	1.4967	1.5521	1.5644
O2	0.0121	0.0024	0.0005	0.0000
OH	0.0999	0.0333	0.0142	0.0017
F2	0.0000	0.0000	0.0000	0.0000
BF	0.3383	0.0763	0.0237	0.0041
BF2	0.0207	0.0045	0.0016	0.0006
BF3	0.0062	0.0018	0.0009	0.0008
BOF	1.0491	1.3666	1.4243	1.4459
BO	0.0370	0.0046	0.0009	0.0000
B2O2	0.0001	0.0000	0.0000	0.0000
B2O3	0.0000	0.0000	0.0000	0.0000
HB02	0.0111	0.0103	0.0128	0.0128
CONDENSED PHASES				
B2O3/GL	0	0	0	0
B2O3/L	0	0	0	0
B/LIQUID	0	0	0	0
B/SOLID	0	0	0	0

TABLE 107

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	B5H9	40.000		0.6230	298.16
	H2O2	60.000		1.443	298.16
INGREDIENT DATA:	B5H9		HEAT OF FORM.		
	H2O2		7.7400		
			-44.840		
ATOMIC COMPOSITION (GM AT/100GM)					
H		9.2265			
B		3.1660			
O		3.5278			
PROPELLANT ENTHALPY		-74.191	KCAL/100 GM		
PROPELLANT DENSITY		0.9453	CM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)				0.0342	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP (LB-SEC/CU IN)				353.66	396.78
TEMPERATURE (K)				12.079	13.552
CP (CAL/GM-DEG.K)				1624.8	1576.6
MOL. WT.-EFFECTIVE				0.77035	0.76735
CP/CV -EFFECTIVE				20.510	21.344
CF -APPROX.				1.1438	1.1381
PEAE/M (SEC)				1.9862	2.2284
AE/AT -APPROX.				21.750	16.094
				61.079	451.96
FROZEN EQUILIBRIA					
ISP (SEC)				327.36	355.38
TEMPERATURE (K)				976.95	636.07
C* (FT/SEC)					
CF					
PEAE/M (SEC)				1.6387	1.9959
AE/AT				14.571	8.7407
				40.919	245.45

TABLE 108

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.070	0.2000
2684.9	2050.8	1824.8	1576.6
-74.191	-179.69	-217.93	-255.12
325.06	325.06	325.06	325.06
76.354	77.004	77.095	76.735
5.6484	5.0977	4.8756	4.6850
0.0310	0.0108	0.0056	0.0017
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
4.0552	4.3814	4.4834	4.5713
0.0121	0.0014	0.0005	0.0001
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0072	0.0009	0.0002	0.0000
0.3675	0.1809	0.0898	0.0186
0.1145	0.0723	0.0430	0.0114
1.0606	0.4500	0.2532	0.0820
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.1027	0.6822	0.9040	1.0974
0.9284	0	0	0
0	0.8442	0.6389	0.6291

PRESSURE (PSI)

TEMPERATURE (KELVIN)

ENTHALPY (KILOCALORIES)

ENTROPY (CALORIES/DEG.K)

HEAT CAPACITY (CAL/K)

MOLES OF GAS

MOLECULAR COMPOSITION:

H

B

O

H2

H2O

O2

OH

BO

B2O2

B2O3

HBO2

H3BO3

H3BO6

B2

BH

CONDENSED PHASES

B2O3/L/

B/LIQUID/

B/SOLID/

TABLE 109

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	N2O4	75.500		1.430	298.16
	B5H9	24.500		0.6230	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	N2O4		-5.4000		
	B5H9		7.7400		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	3.4905			
	B	1.9392			
	N	1.6410			
	O	3.2820			
PROPELLANT ENTHALPY		-1.4289	KCAL/100 GM		
PROPELLANT DENSITY		1.086	GM/CC		
				0.0392	LB/CU IN
PRESSURE (PSI)		CHAMBER	EXHAUST	EXHAUST	EXHAUST
SHIFTING EQUILIBRIA		1000.0	14.70	2.000	0.2000
ISP (SEC)			304.09	350.34	387.39
IVSP(LB-SEC/CU IN)			11.926	13.740	15.193
TEMPERATURE (K)		4114.6	2722.2	2164.1	1820.4
CP (CAL/GM-DEG.K)		0.49659	0.48456	0.47498	0.47074
MOL. WT.-EFFECTIVE		25.619	27.645	28.152	29.336
CP/CV -EFFECTIVE		1.1851	1.1742	1.1746	1.1681
CF -APPROX.			1.6661	1.9195	2.1225
PEAF/M (SEC)			27.997	19.146	13.849
AE/AT -APPROX.			10.438	52.450	379.40
FROZEN EQUILIBRIA					
ISP (SEC)			292.36	334.82	363.96
TEMPERATURE (K)		4114.6	2095.8	1434.3	878.09
C* (FT/SEC)		5872.2			
CF			1.6013	1.6344	1.6942
PEAF/M (SEC)			24.191	14.457	8.1416
AE/AT			9.0190	39.605	223.04

CASE BASIS: 100 GM PROPELLANT		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)		4114.6	2722.2	2164.1	1820.4
ENTHALPY (KILOCALORIES)		-1.4289	-107.70	-142.49	-173.90
ENTROPY (CALORIES/DEG.K)		267.34	267.34	267.34	267.34
HEAT CAPACITY (CAL/K)		49.659	48.458	47.496	47.074
MOLES OF GAS		3.9033	3.6173	3.5522	3.4088
MOLECULAR COMPOSITION:					
H		0.4302	0.1224	0.0286	0.0074
B		0.0037	0.0001	0.0000	0.0000
N		0.0006	0.0000	0.0000	0.0000
O		0.0054	0.0000	0.0000	0.0000
H2		0.8693	1.0930	1.1883	1.2186
H2O		0.0603	0.0101	0.0028	0.0012
O2		0.0002	0.0000	0.0000	0.0000
OH		0.0199	0.0003	0.0000	0.0000
N2		0.8179	0.8205	0.8205	0.7914
NO		0.0036	0.0000	0.0000	0.0000
BN		0.0000	0.0000	0.0000	0.0000
BO		0.2671	0.0411	0.0051	0.0005
B2O2		0.1666	0.1972	0.1668	0.0619
B2O3		0.0777	0.1711	0.2604	0.2844
HBO2		1.1795	1.1614	1.0796	1.0434
H3BO3		0.0000	0.0000	0.0000	0.0000
HBB3O6		0.0000	0.0000	0.0000	0.0000
NH3		0.0008	0.0000	0.0000	0.0000
NH4		0.0003	0.0000	0.0000	0.0000
NH3		0.0000	0.0000	0.0000	0.0000
B2		0.0000	0.0000	0.0000	0.0000
BH		0.0002	0.0000	0.0000	0.0000
CONDENSED PHASES					
B2O3/L/		0	0	0	0.0721
BN/SOLID/		0	0	0	0.0583
B/LIQUID/		0	0	0	0
B/SOLID/		0	0	0	0

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CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
NF3		87.000		1.532	144.00
B5H9		13.000		0.6230	298.16
INGREDIENT DATA:					
NF3	NF3		HEAT OF FORM.		
B5H9	B5H9		-32.000		
			7.7400		
ATOMIC COMPOSITION (GM AT/100GM)					
H		1.8521			
B		1.0289			
N		1.2252			
F		3.6756			
PROPELLANT ENTHALPY					
-37.814 KCAL/100 GM					
PROPELLANT DENSITY					
1.288 GM/CC					
PRESSURE (PSI)					
CHAMBER 1000.0 EXHAUST 14.70					
SHIFTING EQUILIBRIA					
ISP (SEC)					
IVSP (LB-SEC/CU IN) 326.21					
TEMPERATURE (K) 15.177					
CP (CAL/GM-DEG.K) 3154.5					
MOL. WT.-EFFECTIVE 0.35402					
CP/CV -EFFECTIVE 28.767					
CF -APPROX. 1.2726					
PEAE/M (SEC) 1.6887					
AE/AT -APPROX. 29.063					
FROZEN EQUILIBRIA					
ISP (SEC) 300.37					
TEMPERATURE (K) 1889.0					
C* (FT/SEC) 4809.1					
CF (SEC) 6215.1					
PEAF/M (SEC) 21.402					
AE/AT 7.5390					

TABLE 112

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4809.1	3154.5	2500.5	2040.9
TEMPERATURE (KELVIN)	-37.614	-159.91	-197.82	-231.28
ENTHALPY (KILOCALORIES)	241.01	241.01	241.01	241.01
ENTROPY (CALORIES/DEG.K)	36.514	35.402	34.957	34.707
HEAT CAPACITY (CAL/K)	3.9363	3.4762	3.3338	3.1536
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.2360	0.0988	0.0499	0.0189
B	0.0004	0.0000	0.0000	0.0000
N	0.0039	0.0000	0.0000	0.0000
F	0.4776	0.0285	0.0009	0.0008
H2	0.0366	0.0460	0.1608	0.3401
HF	1.5422	1.6614	1.4806	1.1529
N2	0.6104	0.6126	0.6126	0.6126
NH	0.0005	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
BN	0.0000	0.0000	0.0000	0.0000
BF	0.6318	0.4717	0.3757	0.2256
BF2	0.1664	0.1576	0.1413	0.1130
BF3	0.2304	0.3996	0.5119	0.6904
CONDENSED PHASES				
BN/SOLID/	0	0	0	0
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 113

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLF3	89.000		1.810	298.16
	B5H9	11.000		0.6230	298.16
INGREDIENT DATA:	CLF3		HEAT OF FORM.		
	B5H9		-44.400		
ATOMIC COMPOSITION(GM AT/100GM)			7.7400		
	H	1.5671			
	B	0.8706			
	F	2.8878			
	CL	0.9626			
PROPELLANT ENTHALPY		-41.392	KCAL/100 GM		
PROPELLANT DENSITY		1.496	CM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)				0.0541	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)				332.43	367.58
TEMPERATURE (K)				17.972	19.873
CP (CAL/GM-DEG.K)				2554.6	2159.6
MOLE WT.-EFFECTIVE				0.26803	0.28500
CP/CV -EFFECTIVE				36.846	39.222
CF -APPROX.				1.2304	1.2162
PEAF/M (SEC)				1.9367	2.1415
AE/AT -APPROX.				18.032	12.951
				52.525	377.24
FROZEN EQUILIBRIA					
ISP (SEC)				299.24	316.64
TEMPERATURE (K)				985.66	504.17
C* (FT/SEC)					
CF					
PEAE/M (SEC)				1.7434	1.8443
AE/AT				9.4281	4.5571
				27.464	132.77

TABLE 114

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4542.0	3007.2	2554.6	2159.0
TEMPERATURE (KELVIN)	-41.392	-137.67	-168.40	-196.60
ENTHALPY (KILOCALORIES)	201.36	201.36	201.36	201.36
ENTROPY (CALORIES/DEG.K)	29.781	29.063	28.803	28.500
HEAT CAPACITY (CAL/K)	3.3107	2.8828	2.7140	2.5495
MOLES OF GAS	0.1325	0.0430	0.0235	0.0113
MOLECULAR COMPOSITION:	0.0001	0.0000	0.0000	0.0000
H	0.2176	0.0109	0.0018	0.0002
O	0.6771	0.4578	0.3014	0.1450
F	0.0272	0.0248	0.0275	0.0343
CL	0.2430	0.4638	0.6191	0.7780
H2	1.1172	1.0107	0.8696	0.7085
HCL	0.0000	0.0000	0.0000	0.0000
HF	0.0038	0.0011	0.0005	0.0001
F2	0.0015	0.0000	0.0000	0.0000
CL2	0.0006	0.0000	0.0000	0.0000
CLF	0.0001	0.0000	0.0000	0.0000
BCL	0.0000	0.0000	0.0000	0.0000
BCL2	0.0000	0.0000	0.0000	0.0000
BCL3	0.0000	0.0000	0.0000	0.0000
BF	0.4488	0.2901	0.2218	0.1524
BF2	0.1422	0.1237	0.1087	0.0890
BF3	0.2478	0.4201	0.5012	0.5929
BFCL	0.0057	0.0029	0.0020	0.0011
BF2CL	0.0238	0.0318	0.0348	0.0333
BFCL2	0.0014	0.0019	0.0021	0.0019
B2	0.0000	0.0000	0.0000	0.0000
BH	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES	0	0	0	0
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 115

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLO3F	77.000		1.430	298.16
	B5H9	23.000		0.6230	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	CLO3F	-10.100			
	B5H9	7.7400			
ATOMIC COMPOSITION (GM AT/100GM)					
	H	3.2768			
	B	1.8204			
	O	2.2546			
	F	0.7515			
	CL	0.7515			
PROPELLANT ENTHALPY		-4.7725	KCAL/100 GM		
PROPELLANT DENSITY		1.102	GM/CC		
		1000.0	CHAMBER		
PRESSURE (PSI)			EXHAUST	0.0398	LB/CU IN
SHIFTING EQUILIBRIA				2.000	EXHAUST
ISP (SEC)				348.71	384.85
IVSP (LB-SEC/CU IN)				13.881	15.32
TEMPERATURE (K)				2301.2	1779.2
CP (CAL/GM-DEG.K)				0.40866	0.39952
MOL. WT.-EFFECTIVE				29.956	30.652
CP/CV -EFFECTIVE				1.1938	1.1937
CF -APPROX.				1.9240	2.1234
PEAE/M (SEC)				19.047	13.040
AE/AT -APPROX.				52.544	359.73
FROZEN EQUILIBRIA					
ISP (SEC)				326.43	352.01
TEMPERATURE (K)				1275.5	733.04
C* (FT/SEC)					
CF				1.6010	1.9422
PEAF/M (SEC)				12.802	6.8229
AE/AT				35.317	188.22

TABLE 116

CASE BASIS: 100 GM PROPELLANT			
CHAMBER			
1000.0	EXHAUST	EXHAUST	EXHAUST
4254.2	14.70	2.000	0.2000
-4.7725	2820.6	2301.2	1779.2
248.07	-110.19	-144.52	-174.99
42.590	248.07	248.07	248.07
3.7896	41.564	40.866	39.952
	3.4386	3.3382	3.2624
MOLECULAR COMPOSITION:			
H	0.1604	0.0492	0.0049
B	0.0003	0.0000	0.0000
O	0.0062	0.0000	0.0000
F	0.0004	0.0000	0.0000
CL	0.1838	0.0190	0.0018
H2	0.8002	1.0436	1.1276
H2O	0.0399	0.0014	0.0002
HCL	0.5080	0.7058	0.7119
HF	0.0227	0.0006	0.0001
O2	0.0001	0.0000	0.0000
OH	0.0179	0.0000	0.0000
F2	0.0000	0.0000	0.0000
CL2	0.0004	0.0000	0.0000
CLO	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000
BCl	0.0173	0.0033	0.0006
BCl2	0.0010	0.0010	0.0010
BCl3	0.0001	0.0011	0.0091
BF	0.1700	0.0957	0.0512
BF2	0.0002	0.0000	0.0000
BF3	0.0000	0.0000	0.0000
BFCL	0.0009	0.0002	0.0002
BF2CL	0.0000	0.0000	0.0000
BFCL2	0.0001	0.0000	0.0000
BOCL	0.0380	0.0176	0.0069
BOF	0.5369	0.6546	0.5997
BO	0.2523	0.0117	0.0005
B2O2	0.0922	0.1687	0.1810
B2O3	0.0262	0.1032	0.1610
HB02	0.5399	0.4310	0.3042
CONDENSED PHASES			
B2O3/L	0	0	0.0313
B/LIQUID	0	0	0
B/SOLID	0	0	0

TABLE 117

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	B5H9	25.000			
	NO2CLO4	75.000			
INGREDIENT DATA:			HEAT OF FORM.		
	B5H9		7.7400	0.6230	298.16
	NO2CLO4		8.0000	2.220	298.16
ATOMIC COMPOSITION(GM AT/100GM)					
	H	3.5617			
	B	1.9787			
	N	0.5156			
	O	3.0935			
	CL	0.5156			
PROPELLANT ENTHALPY		7.1878	KCAL/100 GM		
PROPELLANT DENSITY		1.353	GM/CC		
		CHAMBER			
		1000.0			
PRESSURE (PSI)				0.0489	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAF/M (SEC)					
AE/AT					

TABLE 118

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
GASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4175.0	2817.8	2328.5	1876.4
TEMPERATURE (KELVIN)	7.1878	-96.146	-130.52	-161.75
ENTHALPY (KILOCALORIES)	255.38	255.38	255.38	255.38
ENTROPY (CALORIES/DEG.K)	46.610	45.584	44.832	43.861
HEAT CAPACITY (CAL/K)	3.7414	3.4232	3.3298	3.2391
MOLES OF GAS	0.4532	0.1603	0.0572	0.0108
MOLECULAR COMPOSITION:	0.0064	0.0003	0.0000	0.0000
H	0.0004	0.0000	0.0000	0.0000
B	0.0053	0.0000	0.0000	0.0000
N	0.1098	0.0408	0.0147	0.0028
O	0.8274	0.9968	1.0721	1.1192
CL	0.0466	0.0077	0.0025	0.0006
H2	0.3520	0.4450	0.4828	0.5045
H2O	0.2576	0.2578	0.2578	0.2310
HCL	0.0140	0.0048	0.0018	0.0003
N2	0.0006	0.0004	0.0003	0.0002
BCL	0.0001	0.0001	0.0002	0.0005
BCL2	0.0383	0.0239	0.0150	0.0062
BCL3	0.3316	0.0740	0.0169	0.0014
BOCL	0.2142	0.2986	0.2939	0.1930
BO	0.0755	0.1652	0.2421	0.3619
B2O2	1.0084	0.9474	0.8725	0.8068
B2O3	0	0	0	0
HB02	0	0	0	0
CONDENSED PHASES	0	0	0	0
B2O3/L/	0	0	0	0.0536
BN/SOLID/	0	0	0	0
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 119

[illegible]

TABLE 120

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASES: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3109.2	2124.3	1874.7	1610.9
ENTHALPY (KILOCALORIES)	-43.389	-135.22	-166.85	-197.18
ENTROPY (CALORIES/DEG-K)	270.86	270.86	270.86	270.86
HEAT CAPACITY (CAL/K)	53.793	52.608	53.112	53.571
MOLES OF GAS	4.4882	4.0975	3.8967	3.7223
MOLECULAR COMPOSITION:				
H	0.0814	0.0105	0.0052	0.0015
B	0.0004	0.0000	0.0000	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0130	0.0019	0.0009	0.0002
H2	2.1241	2.0794	2.0217	2.3638
H2O	0.0153	0.0046	0.0028	0.0017
HCL	0.5939	0.6526	0.6600	0.6631
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
N2	0.3318	0.2071	0.2115	0.2506
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
BN	0.0000	0.0000	0.0000	0.0000
BCl	0.0131	0.0002	0.0000	0.0000
BCl2	0.0035	0.0003	0.0000	0.0000
BCl3	0.0027	0.0012	0.0004	0.0001
BO	0.0287	0.0050	0.0016	0.0002
B2O	0.0320	0.0008	0.0001	0.0000
B2O3	0.3294	0.0604	0.0143	0.0010
H3BO3	0.0835	0.1149	0.0626	0.0159
HBO2	0.0347	0.0566	0.0714	0.0341
H3BO3	0.0000	0.0000	0.0000	0.0000
H3BO3	0.0000	0.0000	0.0000	0.0000
NH	0.0001	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000
B2	0.0000	0.0000	0.0000	0.0000
CH	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
B2O3/L	0	0.0874	0.3345	0.6051
BN/SOLID/	0	0.2497	0.2008	0.1027
B/LIQUID/	0	0	0	0
B/SOLID/	0	0	0	0

TABLE 122

CASE
BASIS: 100 GN PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3842.4	2577.1	2234.0	1740.4
18.732	-91.940	-129.36	-164.50
259.26	259.26	259.26	259.26
59.317	56.112	54.097	51.854
4.2882	4.0046	3.9742	3.8685
0.5104	0.1252	0.0662	0.0065
0.0010	0.0000	0.0000	0.0000
0.3088	0.2267	0.2207	0.1743
2.9045	3.2265	3.2617	3.2933
0.1031	0.0023	0.0003	0.0000
0.0000	0.0000	0.0000	0.0000
0.0104	0.0000	0.0000	0.0000
0.0653	0.0186	0.0111	0.0082
0.0231	0.0004	0.0000	0.0000
0.3560	0.4049	0.4141	0.3862
0.0055	0.0001	0.0000	0.0000
0.5401	0.5724	0	0
0	0	0.5702	0.5796
0	0	0	0.0864

TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H

O

AL

H2

H2O

O2

OH

ALH

ALO

AL2O

AL2O2

CONDENSED PHASES

AL2O3/L/

AL2O3/C/

AL/LIQUID/

621

CASE	PROPELLANT COMPOSITION	WEIGHT%	NOLAR	DENSITY	REF. TEMP.
F2	F2	73.500	-3.4670	1.510	85.200
ALH3	ALH3	26.500	10.000	1.720	298.16
INGREDIENT DATA:					
F2	F2				
ALH3	ALH3				
ATOMIC COMPOSITION(GM AT/100GM)					
H		2.6505			
F		3.8684			
AL		0.8835			
PROPELLANT ENTHALPY					
PROPELLANT DENSITY		2.1292	KCAL/100 GM		
	CHAMBER	1.560	GM/CC		
	1000.0		EXHAUST		
			14.70		
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)					
IVSP(LB-SEC/CU IN)		352.55			
TEMPERATURE (K)		19.877			
CP (CAL/GM-DEG.K)		3586.7			
MOL. WT.-EFFECTIVE		0.35861			
CP/CV -EFFECTIVE		23.898			
CF -APPROX.		1.3019			
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)		5316.6			
CF (SEC)		6683.8			
PEAF/M (SEC)					
AE/AT					
O.0564 LB/CU IN					
EXHAUST		404.78			
2.000		22.822			
		2938.7			
		0.33627			
		29.186			
		1.2539			
		1.9485			
		21.506			
		51.762			
		351.04			
		376.94			
		506.74			
		1.8145			
		4.8635			
		25.886			
		117.06			

TABLE 124

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
5316.6	3586.7	2938.7	2322.5
2.1292	-140.71	-186.17	-226.00
243.10	243.10	243.10	243.10
35.861	34.319	33.627	33.016
4.1844	3.6087	3.4262	3.2362
0.7328	0.3783	0.2342	0.0913
0.7604	0.1529	0.0213	0.0008
0.0229	0.0036	0.0011	0.0001
0.1096	0.0782	0.1291	0.2986
1.6979	2.1158	2.1581	1.9621
0.0005	0.0000	0.0000	0.0000
0.4394	0.3601	0.3163	0.2120
0.2915	0.3198	0.3256	0.3205
0.1291	0.2000	0.2405	0.3508
0.0001	0.0000	0.0000	0.0000
0	0	0	0
0	0	0	0

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4574.2	3350.3	2984.9	2629.9
15.202	-109.75	-153.50	-195.92
250.79	250.79	250.79	250.79
38.241	39.276	39.771	40.056
4.1241	3.5862	3.3987	3.2176
0.5433	0.4223	0.3958	0.3540
0.3146	0.1519	0.0958	0.0368
0.0680	0.0224	0.0141	0.0064
0.0291	0.0060	0.0028	0.0010
0.3363	0.2920	0.2793	0.2805
0.2891	0.2894	0.2363	0.1731
1.0456	1.4353	1.6645	1.8867
0.1071	0.0592	0.0320	0.0100
0.3596	0.1801	0.1110	0.0528
0.0000	0.0000	0.0000	0.0000
0.0015	0.0001	0.0000	0.0000
0.5998	0.4298	0.3388	0.2477
0.2683	0.2064	0.1638	0.1221
0.0819	0.0704	0.0568	0.0442
0.0226	0.0071	0.0031	0.0009
0.0509	0.0126	0.0051	0.0013
0.0045	0.0009	0.0003	0.0001
0.0019	0.0003	0.0001	0.0000
0	0	0	0
0	0.1661	0.2478	0.3247
0	0	0	0
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H

O

F

AL

H2

H2O

HF

O2

OH

F2

ALH

ALF

ALF2

ALF3

ALOF

ALO

AL2O

AL2O2

CONDENSED PHASES

ALF3/C/

AL2O3/L/

AL2O3/C/

AL/LIQUID/

TABLE 127

CASE	PROPELLANT COMPOSITION	WEIGHT%	HEAT OF FORM.	DENSITY	REF. TEMP.
	ALH3	56.000	10.000	1.720	298.16
	H2O2	44.000	-44.840	1.443	298.16
	INGREDIENT DATA:	FORMULA			
	ALH3	ALH3			
	H2O2	H2O2			
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	8.1881			
	O	2.5870			
	AL	1.8670			
	PROPELLANT ENTHALPY	-39.330	KCAL/100 GM		
	PROPELLANT DENSITY	1.586	GM/CC		
	CHAMBER	1000.0			
	PRESSURE (PSI)				
	SHIFTING EQUILIBRIA				
	ISP (SEC)			0.0573	LB/CU IN
	IVSP(LB-SEC/CU IN)			EXHAUST	EXHAUST
	TEMPERATURE (K)			2.000	0.2000
	CP (CAL/GM-DEG.K)	3797.9		375.64	421.38
	MOL. WT.-EFFECTIVE	0.70174		21.525	24.146
	CP/CV -EFFECTIVE	21.576		2313.0	1900.8
	CF -APPROX.	1.1511		0.65362	0.62175
	PEAF/M (SEC)			23.396	23.645
	AE/AT -APPROX.			1.1462	1.1563
	FROZEN EQUILIBRIA			1.9453	2.1822
	ISP (SEC)			22.754	16.494
	TEMPERATURE (K)			58.918	427.08
	C* (FT/SEC)			360.86	394.62
	CF (SEC)	3797.9		1535.0	1045.0
	PEAF/M (SEC)	6212.8			
	AE/AT				
				1.8688	2.0436
				17.046	10.611
				44.137	274.76

TABLE 128

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3797.9	2670.9	2313.0	1900.8
ENTHALPY (KILOCALORIES)	-39.330	-159.92	-201.50	-243.7
ENTROPY (CALORIES/DEG.K)	281.89	281.89	281.89	281.89
HEAT CAPACITY (CAL/K)	70.174	67.422	65.362	62.175
MOLES OF GAS	4.6348	4.3287	4.2742	4.2293
MOLECULAR COMPOSITION:				
H	0.5417	0.2101	0.1161	0.0284
O	0.0015	0.0000	0.0000	0.0000
AL	0.1216	0.0648	0.0592	0.0590
H2	3.5871	3.9719	4.0323	4.0789
H2O	0.2129	0.0144	0.0023	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0181	0.0002	0.0000	0.0000
ALH	0.0282	0.0050	0.0028	0.0020
ALO	0.0153	0.0005	0.0001	0.0000
AL2O	0.1055	0.0616	0.0614	0.0611
AL2O2	0.0027	0.0001	0.0000	0.0000
CONDENSED PHASES				
AL2O3/L/	0.7428	0.6367	0.4104	0
AL2O3/C/	0	0	0.4306	0.8420
AL/LIQUID/	0	0	0	0

TABLE 129

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	ALH3	48.000		1.720	298.16
	N2O4	52.000		1.430	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	ALH3	ALH3	10.000		
	N2O4	N2O4	-5.4000		
	ATOMIC COMPOSITION (GM AT/100GM)				
	H	4.5010			
	N	1.1302			
	O	2.2605			
	AL	1.6003			
	PROPELLANT ENTHALPY	12.952	KCAL/100 GM		
	PROPELLANT DENSITY	1.556	CM/CC		
		CHAMBER	EXHAUST	0.0562 LB/CU IN	EXHAUST
		1000.0	14.70	2.000	0.2000
	PRESSURE (PSI)			350.10	400.42
	SHIFTING EQUILIBRIA			20.131	22.510
	ISP (SEC)			27.11.6	2313.0
	IVSP (LB-SEC/CU IN)			0.53800	0.52566
	TEMPERATURE (K)	4226.0		30.435	31.532
	CP (CAL/GM-DEG.K)	0.54976		1.1331	1.1362
	MOL. WT.-EFFECTIVE	26.827		1.9632	2.1952
	CP/CV -EFFECTIVE	1.1557		21.510	15.838
	CF -APPROX.			58.963	434.14
	PEAF/M (SEC)			339.59	371.66
	AE/AT -APPROX.			1683.4	1118.2
	FROZEN EQUILIBRIA				
	ISP (SEC)	4226.0	295.05		
	TEMPERATURE (K)	5868.7	2335.2		
	C* (FT/SEC)			1.8617	2.0375
	CF			15.976	9.6964
	PEAF/M (SEC)			43.792	265.79
	AE/AT				

TABLE 130

CASE		BASIS: 100 GM PROPELLANT			
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)		4226.0	3114.0	2711.6	2313.0
ENTHALPY (KILOCALORIES)		12.952	-95.819	-134.42	-171.32
ENTROPY (CALORIES/DEG.K)		246.41	246.41	246.41	246.41
HEAT CAPACITY (CAL/K)		54.976	54.526	53.800	52.566
MOLES OF GAS		3.7275	3.4117	3.2856	3.1714
MOLECULAR COMPOSITION:					
H		0.7063	0.5780	0.4266	0.2377
N		0.0007	0.0000	0.0000	0.0000
O		0.0181	0.0017	0.0002	0.0000
AL		0.1634	0.0903	0.0680	0.0566
H2		1.7165	2.0143	2.1532	2.2760
H2O		0.2780	0.0904	0.0323	0.0052
O2		0.0012	0.0000	0.0000	0.0000
OH		0.0799	0.0098	0.0017	0.0001
N2		0.5594	0.5648	0.5651	0.5651
NO		0.0039	0.0006	0.0001	0.0000
ALH		0.0233	0.0036	0.0016	0.0007
ALO		0.0565	0.0091	0.0023	0.0003
AL2O		0.1054	0.0482	0.0343	0.0296
AL2O2		0.0081	0.0008	0.0002	0.0000
ALN		0.0001	0.0000	0.0000	0.0000
NH		0.0011	0.0000	0.0000	0.0000
NH2		0.0006	0.0000	0.0000	0.0000
NH3		0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES					
ALN/C/		0	0	0	0
AL2O3/L/		0.5650	0.6996	0.7297	0.6677
AL2O3/C/		0	0	0	0.0741
AL/LIQUID/		0	0	0	0

TABLE 131

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	ALH3	17.000		1.720	298.16
	NF3	83.000		1.532	144.00
INGREDIENT DATA:	ALH3		HFAT OF FORM.		
	NF3		10.000		
			-32.000		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	1.7003			
	N	1.1689			
	F	3.5066			
	AL	0.5668			
PROPELLANT ENTHALPY		-31.736	KCAL/100 GM		
PROPELLANT DENSITY		1.561	GM/CC		
	CHAMBER	1000.0	EXHAUST	0.0564	LB/CU IN
PRESSURE (PSI)			14.70	EXHAUST	0.2000
SHIFTING EQUILIBRIA					
ISP (SEC)					
IVSP(LB-SEC/CU IN)					
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAE/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF (SEC)					
PEAE/M (SEC)					
AE/AT					

TABLE 132

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4984.8	3398.4	2828.2	1977.4
-31.736	-146.73	-186.69	-219.66
222.81	222.81	222.81	222.81
33.160	32.060	31.573	30.616
3.6245	3.1527	3.0059	2.9576
0.2098	0.0428	0.0036	0.0000
0.0056	0.0002	0.0000	0.0000
0.7909	0.3038	0.1548	0.1060
0.0018	0.0000	0.0000	0.0000
0.0209	0.0027	0.0004	0.0000
1.4488	1.6522	1.6909	1.7003
0.5816	0.5844	0.5844	0.5844
0.0000	0.0000	0.0000	0.0000
0.1123	0.0197	0.0018	0.0000
0.2037	0.1102	0.0359	0.0000
0.2490	0.4369	0.3291	0.5668
0.0000	0.0000	0.0000	0.0000
0.0001	0.0000	0.0000	0.0000
0	0	0	0
0	0	0	0
0	0	0	0

CONDENSED PHASES
ALF3/C/
ALN/C/
AL/LIQUID/

TABLE 133

PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
CLF3	64.000		1.810	298.16
ALH3	36.000		1.720	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
CLF3	CLF3	-44.400		
ALH3	ALH3	10.000		
ATOMIC COMPOSITION (GM AT/100GM)				
H	3.6007			
F	2.6766			
AL	1.2002			
CL	0.6922			
PROPELLANT ENTHALPY		KCAL/100 GM		
PROPELLANT DENSITY		GM/CC		
	-18.732	EXHAUST	0.0642 LB/CU IN	
	1.776	CHAMBER	EXHAUST	0.2000
	1000.0			
PRESSURE (PSI)				
SHIFTING EQUILIBRIA				
ISP (SEC)	284.76		325.50	357.93
IVSP (LB-SEC/CU IN)	18.278		20.893	22.974
TEMPERATURE (K)	2418.0		1971.3	1574.4
CP (CAL/GM-DEG.K)	0.34124		0.33684	0.33103
MOL. WT.-EFFECTIVE	29.620		31.014	32.450
CP/CV -EFFECTIVE	1.2447		1.2749	1.2270
CF -APPROX.	1.6585		1.8057	2.0846
PEAE/M (SEC)	24.765		16.893	11.720
AE/AT -APPROX.	9.8222		49.152	341.28
FROZEN EQUILIBRIA				
ISP (SEC)	267.02		296.94	317.47
TEMPERATURE (K)	1555.6		897.52	458.06
C* (FT/SEC)	3949.3			
CF	5524.4			
PEAE/M (SEC)	1.5551		1.7405	1.8489
AE/AT	19.017		9.8040	4.7101
	7.5366		28.549	137.16

TABLE 134

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3949.3	2418.0	1971.3	1574.4
TEMPERATURE (KELVIN)	-18.732	-111.92	-140.50	-165.97
ENTHALPY (KILOCALORIES)	222.25	222.25	222.25	222.25
ENTROPY (CALORIES/DEG.K)	35.576	34.124	33.684	33.103
HEAT CAPACITY (CAL/K)	3.7758	3.3761	3.2244	3.0817
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.3575	0.0379	0.0081	0.0008
F	0.0052	0.0000	0.0000	0.0000
AL	0.0224	0.0008	0.0001	0.0000
CL	0.0659	0.0052	0.0008	0.0000
H2	1.0935	1.4300	1.5774	1.7193
HCL	0.3541	0.3432	0.2629	0.1175
HF	0.6991	0.3595	0.1749	0.0438
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0001	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
ALH	0.0029	0.0000	0.0000	0.0000
ALCL	0.1576	0.1328	0.1134	0.0896
ALCL2	0.0087	0.0181	0.0278	0.0407
ALCL3	0.0011	0.0065	0.0186	0.0520
ALF	0.6302	0.4272	0.2992	0.1893
ALF2	0.2290	0.3092	0.3179	0.2972
ALF3	0.0579	0.1620	0.2432	0.3268
ALFCL2	0.0033	0.0118	0.0237	0.0431
ALF2CL	0.0200	0.0418	0.0571	0.0641
ALFCL	0.0570	0.0900	0.0993	0.0974
CONDENSED PHASES				
ALF3/C/	0	0	0	0
AL/LIQUID/	0	0	0	0

TABLE 135

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	ALH3	45.000		1.720	298.16
	CLO3F	55.000		1.430	298.16
INGREDIENT DATA:	FORMULA	H=AT OF FORM.			
	ALH3		10.000		
	CLO3F		-10.100		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	4.5009			
	O	1.6104			
	F	0.5368			
	AL	1.5003			
	CL	0.5368			
PROPELLANT ENTHALPY		9.5812	KCAL/100 GM		
PROPELLANT DENSITY		1.547	GM/CC		
	CHAMBER		EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)				0.0559	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	0.2000
ISP (SEC)				349.42	389.97
IVSP(LB-SEC/CU IN)				19.535	21.802
TEMPERATURE (K)				2620.9	2306.6
CP (CAL/GM-DEG.K)		4204.9		0.45653	0.44305
MOL. WT.-EFFECTIVE		0.46445		31.614	32.113
CP/CV -EFFECTIVE		27.452		1.1597	1.1624
CF -APPROX.		1.1846		1.9600	2.1875
PEAE/M (SEC)				20.513	15.924
AE/AT -APPROX.				57.535	446.64
FROZEN EQUILIBRIA				325.43	352.67
ISP (SEC)				1431.7	898.66
TEMPERATURE (K)		4204.9			
C* (FT/SEC)		5735.6			
CF					
PEAF/M (SEC)				1.8255	1.9783
AE/AT				13.855	8.0252
				38.861	225.08

TABLE 136

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4204.9	3041.5	2620.9	2306.6
TEMPERATURE (KELVIN)	9.5812	-94.577	-130.73	-165.19
ENTHALPY (KILOCALORIES)	233.13	233.13	233.13	233.13
ENTROPY (CALORIES/DEG.K)	46.445	46.271	45.653	44.305
HEAT CAPACITY (CAL/K)	3.6427	3.2925	3.1632	3.1140
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.6024	0.4185	0.2650	0.2045
O	0.0236	0.0016	0.0001	0.0000
F	0.0023	0.0003	0.0000	0.0000
AL	0.0849	0.0212	0.0080	0.0037
CL	0.0624	0.0455	0.0303	0.0236
H2	1.3677	1.6490	1.7768	1.8294
H2O	0.3192	0.1252	0.0566	0.0239
HCL	0.2488	0.3147	0.3484	0.3703
HF	0.1780	0.2082	0.2189	0.2190
O2	0.0022	0.0000	0.0000	0.0000
OH	0.0979	0.0111	0.0018	0.0004
ClO	0.0001	0.0000	0.0000	0.0000
ClF	0.0000	0.0000	0.0000	0.0000
ALCL	0.2255	0.1766	0.1581	0.1429
ALF	0.3157	0.2902	0.2756	0.2733
ALF2	0.0192	0.0178	0.0197	0.0203
ALF3	0.0008	0.0008	0.0010	0.0011
ALO	0.0420	0.0034	0.0005	0.0001
AL2O	0.0450	0.0081	0.0024	0.0008
AL2O2	0.0049	0.0002	0.0000	0.0000
CONDENSED PHASES				
ALF3/C/	0	0	0	0
AL2O3/L/	0.3561	0.4868	0.5164	0.5284
AL2O3/G/	0	0	0	0
AL/LIQUID/	0	0	0	0

TABLE 137

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	ALH3	58.000		1.720	298.16
	NO2CLO4	42.000		2.220	298.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
ALH3	ALH3	10.000			
NO2CLO4	NO2CLO4	8.0000			
ATOMIC COMPOSITION (GM AT/100GM)					
H		5.6012			
N		0.2887			
O		1.7324			
AL		1.9337			
CL		0.2887			
PROPELLANT ENTHALPY		21.647	KCAL/100 GM		
PROPELLANT DENSITY		1.900	GM/CC		
	CHAMBER	1000.0	EXHAUST	0.0686	LB/CU IN
				EXHAUST	0.2000
PRESSURE (PSI)				345.52	384.98
SHIFTING EQUILIBRIA				23.715	26.424
ISP (SEC)				2140.8	1866.0
IVSP (LB-SEC/CU IN)				0.48966	0.48789
TEMPERATURE (K)				26.653	28.083
CP (CAL/GM-DEG.K)				1.1796	1.1696
MOL. WT.-EFFECTIVE				1.9306	2.1512
CP/CV -EFFECTIVE				20.098	14.922
CF -APPROX.				56.150	416.89
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)				329.18	356.90
TEMPERATURE (K)				1337.7	856.36
C* (FT/SEC)					
CF				1.8393	1.6942
PEAF/M (SEC)				14.212	8.3916
AE/AT				39.705	234.45

TABLE 138

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3756.6	2510.1	2140.8	1866.0
TEMPERATURE (KELVIN)	21.647	-80.941	-115.56	-145.69
ENTHALPY (KILOCALORIES)	245.85	245.85	245.35	245.85
ENTROPY (CALORIES/DEG.K)	53.668	50.898	48.966	48.789
HEAT CAPACITY (CAL/K)	4.0451	3.7803	3.7516	3.5609
MOLES OF GAS	0.4251	0.0860	0.0355	0.0168
MOLECULAR COMPOSITION:	0.0001	0.0000	0.0000	0.0000
H	0.0008	0.0000	0.0000	0.0000
N	0.4261	0.1438	0.1365	0.1161
O	0.0053	0.0002	0.0000	0.0000
AL	2.5431	2.8451	2.8774	2.8898
CL	0.0896	0.0015	0.0001	0.0000
H2	0.0558	0.0096	0.0026	0.0010
HCL	0.0000	0.0000	0.0000	0.0000
O2	0.0085	0.0000	0.0000	0.0000
OH	0.1438	0.1444	0.1444	0.0735
N2	0.0003	0.0000	0.0000	0.0000
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0473	0.0124	0.0078	0.0038
ALH	0.2242	0.2779	0.2835	0.2875
ALCl	0.0015	0.0005	0.0002	0.0001
ALCl2	0.0000	0.0000	0.0000	0.0000
ALCl3	0.0003	0.0000	0.0000	0.0000
AL2CL	0.0171	0.0002	0.0000	0.0000
ALO	0.2526	0.2568	0.2617	0.1722
AL2O	0.0039	0.0000	0.0000	0.0000
AL2O2	0.0000	0.0000	0.0000	0.0000
AL2O3	0.0002	0.0000	0.0000	0.0000
NH	0.0002	0.0000	0.0000	0.0000
NH2	0.0001	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES	0	0	0	0.1416
ALN/C/	0.4521	0.4906	0	0
AL2O3/L/	0	0	0	0.3200
AL2O3/C/	0	0	0.4902	0
AL/LIQUID/	0	0	0	0

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[illegible]

TABLE 110

CASE BASIS: 100 GM PROPELLANT				CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)				1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)				3833.0	2684.0	2313.0	1912.3
ENTHALPY (KILOCALORIES)				-20.265	-125.24	-161.30	-197.40
ENTROPY (CALORIES/DEG.K)				251.62	251.62	251.62	251.62
HEAT CAPACITY (CAL/K)				57.128	55.387	53.961	51.579
MOLES OF GAS				4.0231	3.7376	3.6768	3.6303
MOLECULAR COMPOSITION:							
H				0.4445	0.1712	0.0902	0.0241
N				0.0001	0.0000	0.0000	0.0000
O				0.0031	0.0000	0.0000	0.0000
AL				0.0447	0.0038	0.0010	0.0001
CL				0.0269	0.0124	0.0070	0.0019
H2				2.4327	2.7592	2.6287	2.6771
F2O				0.2830	0.0659	0.0226	0.0018
HCL				0.2593	0.3526	0.3824	0.3935
O2				0.0001	0.0000	0.0000	0.0000
OH				0.0303	0.0011	0.0001	0.0000
N2				0.2456	0.2468	0.2468	0.2468
NO				0.0016	0.0000	0.0000	0.0000
CL2				0.0000	0.0000	0.0000	0.0000
CLO				0.0000	0.0000	0.0000	0.0000
ALH				0.0090	0.0003	0.0000	0.0000
ALCL				0.1938	0.1170	0.0918	0.0743
ALCL2				0.0059	0.0050	0.0051	0.0082
ALCL3				0.0004	0.0005	0.0006	0.0025
ALOCL				0.0010	0.0000	0.0000	0.0000
ALO				0.0113	0.0002	0.0000	0.0000
AL2O				0.0280	0.0015	0.0003	0.0000
AL2O2				0.0014	0.0000	0.0000	0.0000
ALN				0.0000	0.0000	0.0000	0.0000
NH				0.0004	0.0000	0.0000	0.0000
NH2				0.0003	0.0000	0.0000	0.0000
NH3				0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES							
ALN/C/				0	0	0	0
AL2O3/L/				0.5377	0.6352	0.3551	0
AL2O3/C/				0	0	0.2954	0.6576
AL/LIQUID/				0	0	0	0

TABLE 141

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEN.
	BEH2	30.000			298.16
	O2	70.000		1.142	90.200
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	BEH2	BEH2	10.000		
	O2	O2	-3.0800		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	5.4402			
	BE	2.7201			
	O	4.3750			
	PROPELLANT ENTHALPY	20.464	KCAL/100 GM		
		CHAMBER	EXHAUST		
		1000.0	14.70		
	PRESSURE (PSI)			EXHAUST	EXHAUST
	SHIFTING EQUILIBRIA			2.000	0.2000
	ISP (SEC)			394.64	444.53
	IVSP(LB-SEC/QU IN)				
	TEMPERATURE (K)	4611.0	3418.3	3033.2	2746.8
	CP (CAL/GM-DEG.K)	0.70046	0.70354	0.70235	0.69923
	MOL. WT.-EFFECTIVE	24.280	26.385	27.451	26.408
	CP/CV -EFFECTIVE	1.1323	1.1199	1.1149	1.1206
	CF -APPROX.		1.6768	1.9558	2.2031
	PEAE/M (SEC)		33.106	24.207	20.230
	AE/AT -APPROX.		11.164	59.984	501.31
	FROZEN EQUILIBRIA				
	ISP (SEC)		330.43	383.01	422.86
	TEMPERATURE (K)		2796.7	2158.0	1599.5
	C* (FT/SEC)	4611.0			
	CF	6491.9			
	PEAE/M (SEC)		1.6376	1.6982	2.0957
	AE/AT		30.138	20.063	13.469
			10.163	49.716	333.75

TABLE 142

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4611.0	3418.3	3033.2	2746.8
TEMPERATURE (KELVIN)	20.464	-111.09	-158.52	-206.64
ENTHALPY (KILOCALORIES)	317.17	317.17	317.17	317.17
ENTROPY (CALORIES/DEG.K)	70.046	70.354	70.235	69.923
HEAT CAPACITY (CAL/K)	4.1186	3.7900	3.6428	3.7868
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.9844	0.9596	0.9073	1.1177
BE	0.0482	0.0174	0.0090	0.0085
O	0.2777	0.2056	0.1678	0.2081
H2	1.0027	1.0262	1.0158	0.9883
H2O	0.6833	0.9022	1.0186	0.9772
O2	0.0750	0.0709	0.0654	0.0819
OH	0.2230	0.3789	0.3119	0.2950
BEH	0.0064	0.0003	0.0001	0.0000
BE0	0.0301	0.0092	0.0044	0.0034
BE02H2	0.0756	0.0441	0.0327	0.0193
BE0H	0.4033	0.1564	0.0856	0.0577
BE2O2	0.0006	0.0003	0.0002	0.0002
BE'03	0.0050	0.0101	0.0112	0.0154
BE4'04	0.0032	0.0079	0.0094	0.0123
BE5'05	0.0003	0.0010	0.0012	0.0015
BE6'06	0.0000	0.0000	0.0000	0.0001
CONDENSED PHASES				
BE02H2/C/	0	0	0	0
BE0/LIQUID/	2.1262	2.4253	2.5094	2.5273
BE0/SOLID/	0	0	0	0
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE 113

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	BEH2	21.000			298.16
	F2	79.000		0	85.200
INGREDIENT DATA:	BEH2		HEAT OF FORM.		
	F2		10.000		
			-3.4670	1.510	
ATOMIC COMPOSITION (GM AT/100GM)					
	H	3.8081			
	BE	1.9041			
	F	4.1579			
PROPELLANT ENTHALPY			KCAL/100 GM		
		11.833	EXHAUST	EXHAUST	EXHAUST
		1000.0	14.70	2.000	0.2000
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
	ISP (SEC)		394.36	453.27	501.18
	IVSP (LB-SEC/CU IN)				
	TEMPERATURE (K)	5194.2	3438.4	2914.7	2425.1
	CP (CAL/GM-DEG.K)	0.46738	0.47241	0.46671	0.45668
	MOL. WT.-EFFECTIVE	18.685	21.253	22.520	23.887
	CP/CV -EFFECTIVE	1.2791	1.2468	1.2332	1.2216
	CF -APPROX.		1.6877	1.9398	2.1448
	PEAF/M (SEC)		35.469	24.687	17.506
	AE/AT -APPROX.		10.329	52.825	374.59
FROZEN EQUILIBRIA					
	ISP (SEC)		362.43	405.81	430.08
	TEMPERATURE (K)	5194.2	1998.6	1142.3	586.33
	C* (FT/SEC)	7518.1			
	CF (SEC)		1.5510	1.7367	1.8405
	PEAF/M (SEC)		25.516	13.025	6.3082
	AE/AT		7.4304	27.871	134.98

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TABLE 114

CASE
BASIS: 100 GM PROPELLANT

	CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	5194.2	3438.4	2914.7	2424.1
ENTHALPY (KILOCALORIES)	11.835	-166.90	-224.28	-276.84
ENTROPY (CALORIES/DEG.K)	302.70	302.70	302.70	302.70
HEAT CAPACITY (CAL/K)	48.738	47.241	46.671	45.868
MOLES OF GAS	5.3520	4.7053	4.4405	4.1863
MOLECULAR COMPOSITION:				
H	1.6210	1.1142	0.7744	0.3849
BE	0.3377	0.1470	0.0662	0.0104
F	0.2038	0.0090	0.0015	0.0002
H2	0.5370	1.0134	1.2727	1.5260
HF	1.0861	0.6646	0.4878	0.3712
BEH	0.0271	0.0025	0.0005	0.0000
BEF	0.2106	0.0247	0.0062	0.0006
BEF2	1.3287	1.7298	1.8312	1.8930
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
BEF2/L/	0	0	0	0
BEF2/C/	0	0	0	0
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE 145

CASE	PROPELLANT COMPOSITION	WEIGHT%	NOLAR	DENSITY	REF.	TEMP.
	OF2	64.000		1.530		128.00
	BEH2	36.000		0		298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
	OF2		3.6000			
	BEH2		10.000			
	ATOMIC COMPOSITION(GM AT/100GM)					
	H	6.5282				
	BE	3.2641				
	O	1.1852				
	F	2.3734				
	PROPELLANT ENTHALPY	KCAL/100 GM				
		CHAMBER	EXHAUST			
		1000.0	14.70			
	PRESSURE (PSI)			EXHAUST		EXHAUST
	SHIFTING EQUILIBRIA			2.000		0.2000
	ISP (SEC)		380.63	442.31		491.00
	IVSP(LB-SEC/CU IN)					
	TEMPERATURE (K)	4128.0	2823.0	2420.4		1869.4
	CP (CAL/GM-DEG.K)	0.68463	0.67746	0.66491		0.64404
	MOL. WT.-EFFECTIVE	16.560	18.028	18.365		18.936
	CP/CV -EFFECTIVE	1.2125	1.1943	1.1044		1.1947
	CF -APPROX.		1.6878	1.9613		2.1772
	PEAF/M (SEC)		35.568	25.762		17.384
	AE/AT -APPROX.		10.732	57.115		385.42
	FOZEN EQUILIBRIA					
	ISP (SEC)		357.26	406.33		436.88
	TEMPERATURE (K)	4128.0	1919.5	1232.6		737.69
	C* (FT/SEC)	7256.0				
	CF		1.5841	1.8017		1.9372
	PEAE/M (SEC)		28.032	15.837		8.8155
	AE/AT		8.4638	35.112		195.45

TABLE 146

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
BE
O
F
H2
H2O
HF
OH
BEH
BEF
BEF2
BE3
BE3H

CONDENSFO PHASES
BE3/LIQUID/
BE3/SOLID/
BE/LIQUID/

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4128.0	2823.0	2420.4	1869.4
36.908	-129.60	-187.93	-240.16
352.41	352.41	352.41	352.41
68.463	67.746	66.481	64.404
6.0386	5.5470	5.4452	5.2810
0.9160	0.3625	0.1962	0.0222
0.8432	0.6837	0.6834	0.6184
0.0014	0.0000	0.0000	0.0000
0.0025	0.0000	0.0000	0.0000
2.4374	3.0335	3.1508	3.2506
0.0266	0.0012	0.0001	0.0000
0.2428	0.0458	0.0161	0.0007
0.0067	0.0000	0.0000	0.0000
0.1508	0.0269	0.0112	0.0040
0.1141	0.0145	0.0046	0.0004
1.0055	1.1551	1.1748	1.1846
0.0076	0.0002	0.0000	0.0000
0.2840	0.0238	0.0030	0.0000
0.8598	0.0273	0	0
0	0.1328	1.1821	1.1852
0	0	0	0.0715

TABLE 148

CASE		BASIS: 100 GM PROPELLANT			
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)		3416.5	2512.0	2077.3	1782.3
ENTHALPY (KILOCALORIES)		-31.706	-193.27	-252.12	-307.12
ENTROPY (CALORIES/DEG.K)		400.40	400.40	400.40	400.40
HEAT CAPACITY (CAL/K)		102.60	99.088	96.388	94.852
MOLES OF GAS		6.6602	6.6092	6.4244	6.0666
MOLECULAR COMPOSITION:					
H		0.3522	0.1607	0.0441	0.0155
BE		0.6556	0.8135	0.6992	0.3607
O		0.0000	0.0000	0.0000	0.0000
H2		5.3970	5.0983	5.6639	5.6981
H2O		0.0030	0.0001	0.0000	0.0000
O2		0.0000	0.0000	0.0000	0.0000
OH		0.0001	0.0000	0.0000	0.0000
BEH		0.1841	0.0330	0.0121	0.0023
BE0		0.0002	0.0000	0.0000	0.0000
BE02H2		0.0002	0.0000	0.0000	0.0000
BE0H		0.0573	0.0036	0.0001	0.0000
BE2O2		0.0000	0.0000	0.0000	0.0000
BE3O3		0.0002	0.0000	0.0000	0.0000
BE4O4		0.0002	0.0000	0.0000	0.0000
BE5O5		0.0000	0.0000	0.0000	0.0000
BE6O6		0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES					
BE02H2/C/		0	0	0	0
BE0/LIQUID/		3.1711	0	0	0
BE0/SOLID/		0	3.2300	3.2336	3.2338
BE/LIQUID/		0	0	0.1351	0.4834
BE/SOLID/		0	0	0	0

TABLE 149

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	BEH2	59.000		0	298.16
	N2O4	41.000		1.430	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	BEH2		10.000		
	N2O4		-5.4000		
	ATOMIC COMPOSITION (GM AT/100GM)				
	H	10.6991			
	BE	5.3495			
	N	0.8911			
	O	1.7823			
	PROPELLANT ENTHALPY				
		51.089	KCAL/100 GM		
	CHAMBER	1000.0	EXHAUST	EXHAUST	EXHAUST
			14.70	2.000	0.2000
	PRESSURE (PSI)				
	SHIFTING EQUILIBRIA				
	ISP (SEC)		344.37	401.44	449.16
	IVSP (LB-SEC/CU IN)				
	TEMPERATURE (K)	3158.1	2304.4	1940.3	1705.7
	CP (CAL/GM-DEG.K)	1.0489	1.0174	1.0038	1.0021
	MOL. WT.-EFFECTIVE	16.660	17.030	17.699	18.247
	CP/CV -EFFECTIVE	1.1283	1.1296	1.1259	1.1219
	CF -APPROX.		1.7060	1.9888	2.2252
	PEAE/M (SEC)		33.972	24.218	17.993
	AE/AT -APPROX.		11.452	59.989	445.70
	FROZEN EQUILIBRIA				
	ISP (SEC)		331.00	382.55	423.20
	TEMPERATURE (K)		1935.0	1508.4	1119.9
	C* (FT/SEC)	3158.1			
	CF	6494.4			
	PEAE/M (SEC)		1.6398	1.8957	2.0966
	AE/AT		30.337	20.457	13.733
			10.227	50.673	340.17

TABLE 150

CASE BASIS: 100 GM PROPELLANT		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)		3158.1	2304.4	1990.3	1795.7
ENTHALPY (KILOCALORIES)		51.089	-85.200	-134.12	-180.77
ENTROPY (CALORIES/DEG.K)		380.18	380.18	380.18	380.18
HEAT CAPACITY (CAL/K)		104.89	101.74	100.38	100.21
MOLES OF GAS		6.0025	5.8720	5.6499	5.4804
MOLECULAR COMPOSITION:					
H		0.1688	0.0551	0.0226	0.0072
BE		0.4665	0.4834	0.2864	0.1269
N		0.0000	0.0000	0.0000	0.0000
O		0.0000	0.0000	0.0000	0.0000
H2		5.1851	5.3110	5.3356	5.3455
H2O		0.0008	0.0000	0.0000	0.0000
O2		0.0000	0.0000	0.0000	0.0000
OH		0.0000	0.0000	0.0000	0.0000
N2		0.0229	0.0006	0.0000	0.0000
NO		0.0000	0.0000	0.0000	0.0000
BEH		0.1335	0.0213	0.0053	0.0008
BEQ		0.0000	0.0000	0.0000	0.0000
BEQ2H2		0.0000	0.0000	0.0000	0.0000
BEQH		0.0195	0.0005	0.0000	0.0000
BE2O2		0.0000	0.0000	0.0000	0.0000
BE3O3		0.0001	0.0000	0.0000	0.0000
BE4O4		0.0000	0.0000	0.0000	0.0000
BE5O5		0.0000	0.0000	0.0000	0.0000
BE6O6		0.0000	0.0000	0.0000	0.0000
NH		0.0000	0.0000	0.0000	0.0000
NH2		0.0000	0.0000	0.0000	0.0000
NH3		0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES					
BE3N2/C/		0.4226	0.4449	0.4455	0.4456
BEQ2H2/C/		0	0	0	0
BEQ/LIQUID/		1.7614	0	0	0
BEQ/SOLID/		0	1.7818	1.7823	1.7823
BE/LIQUID/		1.6952	1.7277	1.7390	0
BE/SOLID/		0	0	0	2.1028

TABLE 151

CASE	PROPELLANT COMPOSITION	WEIGHTS	FORMULA	HFAT OF FORM.	DENSITY	REF. TEMP.
	BEH2	20.000		10.000	0	298.16
	NF3	80.000		-32.000	1.532	144.00
	BEH2		BEH2			
	NF3		NF3			
	ATOMIC COMPOSITION(GM AT/100GM)					
	H	3.6268				
	BE	1.8134				
	N	1.1266				
	F	3.3799				
	PROPELLANT ENTHALPY					
		-17.918	KCAL/100 GM			
	CHAMBER	1000.0	EXHAUST	14.70	EXHAUST	EXHAUST
	PRESSURE (PSI)				2.000	0.2000
	SHIFTING EQUILIBRIA					
	ISP (SEC)				411.88	453.72
	IVSP(LB-SEC/CU IN)					
	TEMPERATURE (K)	4578.3			2459.4	1922.7
	CP (CAL/GM-DEG.K)	0.46266			0.45940	0.45129
	MOL. WT.-EFFECTIVE	19.977			23.331	24.282
	CP/CV -EFFECTIVE	1.2596			1.2276	1.2215
	CF -APPROX.				1.9308	2.1269
	PEAF/M (SEC)				22.127	15.088
	AE/AT -APPROX.				51.864	353.63
	FROZEN EQUILIBRIA					
	ISP (SEC)				374.16	398.68
	TEMPERATURE (K)	4578.3			1096.0	565.26
	C* (FT/SEC)	6863.4				
	CF (SEC)				1.7540	1.8689
	PEAF/M (SEC)				12.677	6.1360
	AE/AT				29.714	143.82

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4578.3	2998.6	2459.4	1922.7
-17.918	-165.60	-212.88	-254.51
289.89	289.89	289.89	289.89
48.266	46.725	45.940	45.129
5.0057	4.4696	4.2861	4.1182
1.0299	0.4097	0.1537	0.0219
0.3272	0.1898	0.1406	0.0615
0.0023	0.0000	0.0000	0.0000
0.0248	0.0002	0.0000	0.0000
0.9848	1.5298	1.7160	1.8006
0.5884	0.1531	0.0397	0.0036
0.5622	0.5633	0.5633	0.5422
0.0390	0.0044	0.0015	0.0002
0.1276	0.0118	0.0025	0.0002
1.3195	1.6073	1.6689	1.6881
0.0000	0.0000	0.0000	0.0000
0	0	0	0.0211
0	0	0	0
0	0	0	0
0	0	0	0
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
BE
N
F
H2
HF
N2
BEH
BEF
BEF2
F2

CONDENSED PHASES
BE3N2/C/
BEF2/L/
BEF2/C/
BE/LIQUID/
BE/SOLID/

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	BEH2	12.000		0	298.16
	CLF3	88.000		1.810	298.16
INGREDIENT DATA:	BEH2		HEAT OF FORM.		
	CLF3		10.000		
ATOMIC COMPOSITION(GM AT/100GM)			-44.400		
	H	2.1761			
	BE	1.0880			
	F	2.8554			
	CL	0.9518			
PROPELLANT ENTHALPY		-31.379	KCAL/100 GM		
		CHAMBER	EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)				EXHAUST	EXHAUST
SHIFTING EQUILIBRIA				2.000	0.2000
ISP (SEC)				367.63	404.68
IVSP(LB-SEC/CU IN)		4960.9			
TEMPERATURE (K)					
CP (CAL/GM-DEG.K)		0.34361		2642.4	2040.0
MOL. WT.-EFFECTIVE		26.816		0.32659	0.31800
CP/CV -EFFECTIVE		1.2750		31.946	33.171
CF -APPROX.				1.2353	1.2321
PEAE/M (SEC)				1.9264	2.1205
AE/AT -APPROX.				19.453	13.139
FROZEN EQUILIBRIA				50.966	344.24
ISP (SEC)					
TEMPERATURE (K)		4960.9		333.75	354.50
C* (FT/SEC)		6140.1		1122.9	574.36
CF					
PEAE/M (SEC)				1.7488	1.8576
AE/AT				10.848	5.2236
				28.421	136.86

TABLE 154

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4960.9	3213.5	2642.4	2040.0
TEMPERATURE (KELVIN)	-31.379	-149.58	-186.70	-219.59
ENTHALPY (KILOCALORIES)	224.62	224.62	224.62	224.62
ENTROPY (CALORIES/DEG.K)	34.361	33.254	32.659	31.800
HEAT CAPACITY (CAL/K)	3.7292	3.2864	3.1303	3.0147
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.6295	0.2777	0.1175	0.0167
BE	0.0418	0.0025	0.0002	0.0000
F	0.1553	0.0072	0.0009	0.0000
CL	0.5035	0.2950	0.1573	0.0294
H2	0.1927	0.2781	0.2921	0.2789
HCL	0.2689	0.5195	0.6859	0.8636
HF	0.6898	0.8227	0.7884	0.7380
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0010	0.0002	0.0001	0.0000
CLF	0.0004	0.0000	0.0000	0.0000
BEH	0.0025	0.0000	0.0000	0.0000
BECL	0.0514	0.0071	0.0011	0.0000
BECL2	0.0073	0.0099	0.0086	0.0041
BEF	0.0494	0.0016	0.0001	0.0000
BEF2	0.8248	0.9570	0.9879	1.0334
BEFCL	0.1110	0.1100	0.0901	0.0504
CONDENSED PHASES				
BEF2/L/	0	0	0	0
BEF2/C/	0	0	0	0
BE/LIQUID/	0	0	0	0
BE/SOLID/	0	0	0	0

TABLE 155

CASE	PROPELLANT COMPOSITION	WEIGHT%	HEAT OF FORM°	DENSITY	REF. TEMP.
BEH2		32.000	10.000	0	298.16
CLO3F		68.000	-10.100	1.430	298.16
INGREDIENT DATA:	FORMULA				
BEH2	BEH2				
CLO3F	CLO3F				
ATOMIC COMPOSITION (GM AT/100GM)					
H		5.8029			
BE		2.9014			
O		1.9911			
F		0.6637			
CL		0.6637			
PROPELLANT ENTHALPY		22.311	KCAL/100 GM		
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
		1000.0	14.70	2.000	0.2000
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)			339.00	395.83	446.12
IVSP (LB-SEC/CU IN)					
TEMPERATURE (K)		4173.0	2997.9	2737.2	2347.3
CP (CAL/GM-DEG.K)		0.65444	0.65324	0.64936	0.63625
MOL. WT.-EFFECTIVE		21.575	23.515	23.333	24.420
CP/CV -EFFECTIVE		1.1636	1.1486	1.1510	1.1467
CF -APPROX.			1.6815	1.9633	2.2128
PEAF/M (SEC)			32.514	25.623	18.629
AE/AT -APPROX.			10.974	63.546	462.00
FROZEN EQUILIBRIA					
ISP (SEC)			325.58	374.63	407.34
TEMPERATURE (K)			2272.4	1633.9	1145.3
C* (FT/SEC)		4173.0			
CF		6486.6			
PEAF/M (SEC)			1.6149	1.8582	2.0204
AE/AT			27.968	17.477	11.267
			9.4395	43.344	279.42

TABLE 156

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4173.0	2997.9	2737.2	2347.3
TEMPERATURE (KELVIN)	22.311	-109.77	-157.75	-206.42
ENTHALPY (KILOCALORIES)	307.00	307.00	307.00	307.00
ENTROPY (CALORIES/DEG.K)	65.444	65.324	64.036	63.625
HEAT CAPACITY (CAL/K)	4.6349	4.2526	4.2858	4.0951
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.7997	0.5074	0.5721	0.3454
BE	0.3376	0.3048	0.3281	0.2906
O	0.0028	0.0001	0.0000	0.0000
F	0.0016	0.0001	0.0000	0.0000
CL	0.0505	0.0246	0.0300	0.0128
H2	2.0931	2.4773	2.4546	2.6298
H2O	0.0518	0.0067	0.0062	0.0007
HCL	0.2318	0.2108	0.2263	0.1710
HF	0.1488	0.0572	0.0499	0.0206
OH	0.0135	0.0006	0.0004	0.0000
BEH	0.0635	0.0093	0.0038	0.0012
BECL	0.2270	0.1708	0.1460	0.1144
BECL2	0.0285	0.0632	0.0668	0.1098
BEF	0.0331	0.0057	0.0032	0.0009
BEF2	0.1914	0.2348	0.2414	0.2462
BEFCL	0.0974	0.1312	0.1277	0.1458
BEQ	0.0070	0.0005	0.0003	0.0000
BEQH	0.2556	0.0457	0.0286	0.0038
CONDENSED PHASES				
BEQ/LIQUID/	1.6602	1.9355	0	0
BEQ/SOLID/	0	0	1.9554	1.9866
BE/LIQUID/	0	0	0	0

TABLE 157

CASE
 PROPELLANT COMPOSITION
 BEH2
 NO2CLO4
 INGREDIENT DATA:
 BEH2
 NO2CLO4
 ATOMIC COMPOSITION(GM AT/100GM)
 H
 BE
 N
 O
 CL
 PROPELLANT ENTHALPY
 WEIGHT%
 43.000
 57.000
 FORMULA
 BEH2
 NO2CLO4
 HEAT OF FORM.
 10.000
 8.0000
 DENSITY
 0
 2.220
 REF. TEMP.
 298.16
 298.16
 MOLAR
 42.123 KCAL/100 GM

PRESSURE (PSI)
 SHIFTING EQUILIBRIA
 ISP (SEC)
 IVSP(LB-SEC/CU IN)
 TEMPERATURE (K)
 CP (CAL/GM-DEG.K)
 MOL. WT.-EFFECTIVE
 CP/CV -EFFECTIVE
 CF -APPROX.
 PEAE/M (SEC)
 AE/AT -APPROX.
 FROZEN EQUILIBRIA
 ISP (SEC)
 TEMPERATURE (K)
 C* (FT/SEC)
 CF
 PEAE/M (SEC)
 AE/AT
 CHAMBER
 1000.0
 3444.4
 0.80791
 17.692
 1.1615
 EXHAUST
 14.70
 345.36
 2573.0
 0.79154
 18.266
 1.1594
 1.7062
 35.264
 11.854
 327.17
 1887.4
 3444.4
 6512.7
 EXHAUST
 2.000
 404.67
 2274.1
 0.78594
 19.277
 1.1510
 1.9992
 25.204
 62.256
 374.53
 1383.9
 1.8502
 18.057
 44.604
 EXHAUST
 0.2000
 454.36
 1973.8
 0.77770
 20.333
 1.1437
 2.2446
 18.471
 456.26
 409.59
 955.66
 2.0235
 11.402
 281.64

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	3444.4	2573.0	2274.1	1973.8
ENTROPY (CALORIES/DEG.K)	42.123	-94.957	-146.08	-195.14
HEAT CAPACITY (CAL/K)	343.72	343.72	343.72	343.72
MOLES OF GAS	80.791	79.154	78.594	77.770
MOLECULAR COMPOSITION:	5.6524	5.4747	5.1875	4.9182
H	0.2827	0.1559	0.1018	0.0506
BE	0.9551	1.0358	0.8822	0.7333
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0022	0.0008	0.0004	0.0001
H2	3.5918	3.7830	3.5276	3.8639
H2O	0.0014	0.0001	0.0000	0.0000
HCL	0.0481	0.0339	0.0267	0.0152
CH	0.0000	0.0000	0.0000	0.0000
N2	0.1793	0.1342	0.0676	0.0071
BEH	0.2330	0.0374	0.0131	0.0039
BECL	0.2811	0.2216	0.1700	0.1114
BECL2	0.0302	0.0678	0.0974	0.1326
BEOH	0.0475	0.0044	0.0008	0.0001
CONDENSED PHASES				
BE3N2/C/	0.0166	0.0617	0.1284	0.1888
BE0/LIQUID/	2.3021	0	0	0
BE0/SOLID/	0	2.3466	2.3503	2.3510
BE/LIQUID/	0	0	0	0

TABLE 159

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	HEAT OF FORM.	DENSITY	REF. TEMP.	EXHAUST
BEH2		32.000	10.000		0	298.16	0.2000
NH4CLO4		68.000	-69.420		1.960	298.16	
INGREDIENT DATA:							
BEH2							
NH4CLO4							
ATOMIC COMPOSITION(GM AT/100GM)							
H		8.1178					
BE		2.9014					
N		0.5787					
O		2.5150					
CL		0.5787					
PROPELLANT ENTHALPY							
		-11.162	KCAL/100 GM				
CHAMBER		1000.0	EXHAUST		2.000		
EXHAUST			14.70				
CHAMBER			339.16		397.58		445.53
EXHAUST			268.6		2242.5		1937.4
CHAMBER		3611.5	0.76737		0.74644		0.73685
EXHAUST		0.78536	19.481		19.976		21.023
CHAMBER		18.963	1.1533		1.1538		1.1472
EXHAUST		1.1540	1.6901		1.9813		2.2202
CHAMBER			35.182		24.412		17.883
EXHAUST			11.930		60.827		445.58
CHAMBER			325.33		372.88		409.38
EXHAUST			2027.7		1510.3		1051.4
CHAMBER		3611.5					
EXHAUST		6456.4					
CHAMBER			1.6212		1.8581		2.0400
EXHAUST			28.416		18.466		11.709
CHAMBER			9.6357		46.011		291.74
EXHAUST							
SHIFTING EQUILIBRIA							
ISP (SEC)							
IVSP(LB-SEC/CU IN)							
TEMPERATURE (K)							
CP (CAL/GM-DEG.K)							
MOL. WT.-EFFECTIVE							
CP/CV -EFFECTIVE							
CF -APPROX.							
PEAE/M (SEC)							
AE/AT -APPROX.							
FROZEN EQUILIBRIA							
ISP (SEC)							
TEMPERATURE (K)							
C* (FT/SEC)							
PEAE/M (SEC)							
AE/AT							

CASE
BASIS: 100 GM PROPELLANT

PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST
TEMPERATURE (KELVIN)	1000.0	14.70	2.000	0.2000
ENTHALPY (KILOCALORIES)	3611.5	2688.6	2242.5	1937.4
ENTROPY (CALORIES/DEG.K)	-11.162	-143.36	-192.83	-239.29
HEAT CAPACITY (CAL/K)	331.74	331.74	331.74	331.74
MOLES OF GAS	78.536	76.737	74.644	73.685
MOLECULAR COMPOSITION:	5.2734	5.1333	5.0061	4.7567
H	0.4009	0.2414	0.0861	0.0392
BE	0.2428	0.2742	0.2600	0.1243
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0126	0.0051	0.0007	0.0002
H2	3.6732	3.6554	3.9842	4.0201
H2O	0.0128	0.0012	0.0000	0.0000
HCL	0.2030	0.1429	0.0585	0.0378
OH	0.0007	0.0000	0.0000	0.0000
N2	0.2893	0.2894	0.2894	0.2353
BEH	0.0606	0.0101	0.0040	0.0007
BECL	0.2300	0.1760	0.1255	0.0577
BECL2	0.0665	0.1274	0.1970	0.2415
BECH	0.0807	0.0103	0.0006	0.0000
CONDENSED PHASES				
BE3/2/C/	0	0	0	0.0541
BE0/LIQUID/	2.2207	0	0	0
BE0/SOLID/	0	2.3035	2.3144	2.3149
BE/LIQUID/	0	0	0	0

TABLE 161

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	LIH	38.000		0.8200	298.16
	O2	62.000		1.142	90.200
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	LIH		-21.600		
	O2		-3.0800		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	4.7811			
	LI	4.7811			
	O	3.8750			
	PROPELLANT ENTHALPY	-109.24	KCAL/100 GM		
	PROPELLANT DENSITY	0.9937	GM/CC		
	CHAMBER	1000.0	EXHAUST	0.0359	LB/CU IN
	EXHAUST		14.70	EXHAUST	0.2000
	PRESSURE (PSI)				
	SHIFTING EQUILIBRIA				
	ISP (SEC)		259.88	302.88	339.49
	IVSP(LB-SEC/CU IN)		9.3305	10.874	12.189
	TEMPERATURE (K)		2215.0	1949.8	1693.8
	CP (CAL/GM-DEG.K)		0.73353	0.73215	0.73015
	MOL. WT.-EFFECTIVE		29.032	29.015	30.409
	CP/CV -EFFECTIVE		1.1029	1.0998	1.0983
	CF -APPROX.		1.6707	1.7471	2.1825
	PEAE/M (SEC)		25.382	18.414	14.185
	AE/AT -APPROX.		11.103	59.190	455.97
	FROZEN EQUILIBRIA				
	ISP (SEC)		258.62	301.67	337.17
	TEMPERATURE (K)		2167.7	1788.4	1424.2
	C* (FT/SEC)				
	CF		1.6626	1.9394	2.1676
	PEAE/M (SEC)		25.059	17.723	12.628
	AE/AT		10.962	56.970	405.91

TABLE 162

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
3195.2	2215.0	1929.8	1693.8
-109.24	-186.86	-214.67	-241.70
306.44	306.44	306.44	306.44
75.719	73.353	73.215	73.015
3.4580	3.4445	3.3428	3.2885
0.0532	0.0100	0.0044	0.0020
0.2586	0.2293	0.1785	0.1511
0.0011	0.0000	0.0000	0.0000
0.7305	0.7810	0.8125	0.8288
0.8838	0.7977	0.8109	0.8185
0.0006	0.0000	0.0000	0.0000
0.0258	0.0015	0.0004	0.0001
0.0026	0.0002	0.0000	0.0000
0.0334	0.0061	0.0023	0.0008
0.0025	0.0002	0.0000	0.0000
0.0261	0.0124	0.0066	0.0036
1.4394	1.6060	1.5270	1.4836
0.0003	0.0001	0.0001	0.0000
1.4946	1.4570	1.5299	1.1370
0	0	0	0.4321
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
LI
O
H2
H2O
O2
OH
LI2
LIH
LIO
LI2O
LIOH
LI2O2H2
CONDENSED PHASES
LI2O/L/
LI2O/SOLID/
LI/LIQUID/

TABLE 163

CASE	PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
	LIH		19.000			
	F2		81.000			
INGREDIENT DATA:	FORMULA		HEAT OF FORM.	DENSITY	REF. TEMP.	
	LIH		-21.600	0.8200	298.16	
	F2		-3.4670	1.510	85.200	
ATOMIC COMPOSITION(GM AT/100GM)						
	H		2.3905			
	LI		2.3905			
	F		4.2632			
PROPELLANT ENTHALPY			-59.026	KCAL/100 GM		
PROPELLANT DENSITY			1.302	GM/CC		
		CHAMBER		EXHAUST		
		1000.0		14.70		
PRESSURE (PSI)				0.0470 LB/CU IN		
SHIFTING EQUILIBRIA				EXHAUST	0.2000	
ISP (SEC)						
IVSP(LB-SEC/CU IN)				406.18		443.22
TEMPERATURE (K)				19.199		20.847
CP (CAL/GM-DEG.K)				1985.8		1599.6
MOL. WT.-EFFECTIVE				0.39487		0.39035
CP/CV -EFFECTIVE				22.776		24.636
CF -APPROX.				1.2836		1.2605
PEAE/M (SEC)				1.6808		2.0422
AE/AT -APPROX.				18.467		12.665
				42.544		291.78
FROZEN EQUILIBRIA						
ISP (SEC)				375.12		396.04
TEMPERATURE (K)				898.88		389.06
C* (FT/SEC)						
CF (SEC)				1.7284		1.8248
PEAE/M (SEC)				10.396		4.2619
AE/AT				23.951		98.187

TABLE 164

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4830.5	2726.0	1985.8	1599.6
TEMPERATURE (KELVIN)	-59.026	-209.24	-250.51	-284.79
ENTHALPY (KILOCALORIES)	290.06	290.06	290.06	290.06
ENTROPY (CALORIES/DEG.K)	43.359	40.496	39.487	39.035
HEAT CAPACITY (CAL/K)	5.0180	4.5610	4.3905	4.0591
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.4719	0.0617	0.0042	0.0005
LI	0.1756	0.0286	0.0022	0.0002
F	0.3580	0.0019	0.0000	0.0000
H2	0.1091	0.2145	0.2557	0.2586
HF	1.6954	1.8995	1.6749	1.8728
LI2	0.0002	0.0000	0.0000	0.0000
LIH	0.0049	0.0002	0.0000	0.0000
LIF	2.1992	2.3501	2.1750	1.6434
LI2F2	0.0003	0.0014	0.0218	0.1038
LI3F3	0.0033	0.0029	0.0565	0.1798
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LIF/LIQUID/	0	0	0	0
LIF/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

TABLE 165

PROPELLANT COMPOSITION		WEIGHT%	MOLAR		
OF2		72.500			
LIH		27.500			
INGREDIENT DATA:		FORMULA	HEAT OF FORM.	DENSITY	REF. TEMP.
OF2		OF2	3.6000	1.530	128.00
LIH		LIH	-21.600	0.8200	298.16
ATOMIC COMPOSITION (GM AT/100GM)					
H		3.4600			
LI		3.4600			
O		1.5426			
F		2.6852			
PROPELLANT ENTHALPY					
PROPELLANT DENSITY		-69.902	KCAL/100 GM		
		1.236	CM/CC		
		CHAMBER	EXHAUST		
		1000.0	14.70		
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
ISP (SEC)				0.0446	LB/CU IN
IVSP (LB-SEC/CU IN)				EXHAUST	EXHAUST
TEMPERATURE (K)				2.000	0.2000
CP (CAL/GM-DEG.K)					
MOL. WT.-EFFECTIVE					
CP/CV -EFFECTIVE					
CF -APPROX.					
PEAE/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA					
ISP (SEC)					
TEMPERATURE (K)					
C* (FT/SEC)					
CF					
PEAE/M (SEC)					
AE/AT					

TABLE 166

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	3843.6	2298.8	1882.3	1582.9
ENTHALPY (KILOCALORIES)	-69.902	-195.21	-232.86	-266.50
ENTROPY (CALORIES/DEG.K)	316.96	316.96	316.96	316.96
HEAT CAPACITY (CAL/K)	51.161	48.625	47.985	47.872
MOLES OF GAS	5.1828	4.7113	4.4316	4.1383
MOLECULAR COMPOSITION:				
H	0.2344	0.0171	0.0034	0.0007
LI	0.4638	0.1744	0.0926	0.0422
O	0.0388	0.0000	0.0000	0.0000
F	0.0033	0.0000	0.0000	0.0000
H2	0.5042	0.6769	0.7259	0.7531
H2O	0.5423	0.6522	0.6285	0.6492
HF	0.3481	0.0939	0.0344	0.0143
OH	0.1486	0.0027	0.0002	0.0000
LI2	0.0026	0.0001	0.0000	0.0000
LIH	0.0336	0.0035	0.0010	0.0002
LIF	2.2076	2.3013	1.9977	1.6559
LI2F2	0.0018	0.0146	0.0490	0.1308
LI3F3	0.0409	0.0869	0.1850	0.2511
LI2C	0.0112	0.0031	0.0017	0.0006
LIOP	0.6012	0.6844	0.7122	0.6400
LI2C2H2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LIF/LIQUID/	0	0	0	0
LI2O/L/	0	0	0	0
LI2C/SOLID/	0	0	0	0.0527

TABLE 167

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	LIH	40.000		0.6200	298.16
	H2O2	60.000		1.443	298.16
INGREDIENT DATA:	FORMULA		HEAT OF FORM.		
	LIH		-21.600		
	H2O2		-44.840		
ATOMIC COMPOSITION (GM AT/100GM)					
	H	8.5605			
	LI	5.0327			
	O	3.5278			
PROPELLANT ENTHALPY		-187.80	KCAL/100 GM		
PROPELLANT DENSITY		1.107	GM/CC		
		CHAMBER	EXHAUST	0.0000 LB/CU IN	
		1000.0	14.70	EXHAUST	0.2000
PRESSURE (PSI)				294.19	340.57
SHIFTING EQUILIBRIA				11.063	13.618
ISP (SEC)				1623.4	1397.8
IVSP (LB-SEC/CU IN)		2334.5		0.96930	0.93745
TEMPERATURE (K)		0.98734		22.411	22.971
CP (CAL/GM-DEG.K)		22.380		1.1007	1.1017
MOL. WT.-EFFECTIVE		1.0988		1.9789	2.2526
CP/CG -EFFECTIVE				20.931	15.448
CF -APPROX.				69.221	510.86
PEAF/M (SEC)					
AE/AT -APPROX.					
FROZEN EQUILIBRIA				292.99	320.50
ISP (SEC)		2334.5		1312.1	1055.7
TEMPERATURE (K)		4864.4			
C* (FT/SEC)					
CF				1.9379	2.1595
PEAF/M (SEC)				17.301	12.491
AE/AT				57.215	413.07

TABLE 168

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	2334.5	1693.8	1623.4	1397.8
TEMPERATURE (KELVIN)	-187.80	-260.99	-290.68	-321.10
ENTHALPY (KILOCALORIES)	336.53	336.53	336.53	336.53
ENTROPY (CALORIES/DEG.K)	98.734	96.998	96.930	93.745
HEAT CAPACITY (CAL/K)	4.4683	4.3913	4.4621	4.3532
MOLES OF GAS	0.0053	0.0005	0.0007	0.0002
MOLECULAR COMPOSITION:	0.0183	0.0052	0.0150	0.0031
H	0.0000	0.0000	0.0000	0.0000
LI	3.2504	3.2656	3.2605	3.2672
O	0.6605	0.9088	0.8531	0.9431
H2	0.0000	0.0000	0.0000	0.0000
H2O	0.0002	0.0000	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0000	0.0000	0.0000	0.0000
LI2	0.0066	0.0004	0.0005	0.0000
LIH	0.0000	0.0000	0.0000	0.0000
LI0	0.0096	0.0001	0.0001	0.0000
LI2O	0.3260	0.2107	0.3321	0.1396
LI0H	0.0001	0.0000	0.0000	0.0000
LI2O2H2	2.3401	2.0276	0	0
CONDENSED PHASES	0	0.3505	2.3424	2.4450
LI2O/L	0	0	0	0
LI2O/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

TABLE 169

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	LIH	26.000		0.8200	298.16
	N2O4	74.000		1.430	298.16
	INGREDIENT DATA:	HEAT OF FORM.			
	LIH		-21.600		
	N2O4		-5.4000		
	ATOMIC COMPOSITION (GM AT/100GM)				
	H	3.2713			
	LI	3.2713			
	N	1.6084			
	O	3.2168			
	PROPELLANT ENTHALPY	-75.002	KCAL/100 GM		
	PROPELLANT DENSITY	1.198	CM/CC		
	CHAMBER	1000.0			
	EXHAUST	14.70			
	PRESSURE (PSI)			0.0433	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	0.2000
	ISP (SEC)		250.08	290.31	324.76
	IVSF (LB-SEC/CU IN)		10.827	12.568	14.060
	TEMPERATURE (K)		2167.7	1868.5	1665.3
	CP (CAL/GM-DEG.K)	3170.5		0.58632	0.53422
	MOL. WT.-EFFECTIVE	0.60000		32.510	32.282
	CP/CV -EFFECTIVE	30.340		1.1164	1.1178
	CF -APPROX.	1.1225		1.9335	2.1629
	PEAF/M (SEC)			17.116	13.733
	AE/AT -APPROX.			56.997	457.30
	FROZEN EQUILIBRIA				
	ISP (SEC)		246.94	286.87	317.75
	TEMPERATURE (K)		1985.2	1557.3	1166.1
	C* (FT/SEC)	3170.5			
	CF	4831.0			
	PEAF/M (SEC)			1.9105	2.1162
	AE/AT			15.469	10.458
				51.512	343.24

TABLE 170

CASE				BASIS: 100 GM PROPELLANT			
				CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)				1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)				3170.5	2167.7	1868.5	1665.3
ENTHALPY (KILOCALORIES)				-75.002	-146.88	-171.86	-196.22
ENTROPY (CALORIES/DEG.K)				274.26	272.26	272.26	272.26
HEAT CAPACITY (CAL/K)				60.000	58.359	58.632	58.422
MOLES OF GAS				3.2960	3.1887	3.0760	3.0976
MOLECULAR COMPOSITION:							
H				0.0179	0.0017	0.0006	0.0003
LI				0.0868	0.0339	0.0198	0.0207
N				0.0000	0.0000	0.0000	0.0000
O				0.0064	0.0001	0.0000	0.0000
H2				0.0993	0.0425	0.0450	0.0441
H2O				0.6336	0.8882	0.9775	0.9565
O2				0.0218	0.0012	0.0001	0.0000
OH				0.0593	0.0046	0.0011	0.0003
N2				0.7945	0.8037	0.8041	0.8042
NO				0.0194	0.0009	0.0001	0.0000
LI2				0.0003	0.0000	0.0000	0.0000
LIH				0.0043	0.0002	0.0001	0.0000
LIO				0.0057	0.0004	0.0001	0.0000
LI2O				0.0230	0.0079	0.0031	0.0021
LI2O2				1.3235	1.4028	1.2242	1.2692
LI2O2H2				0.0002	0.0001	0.0001	0.0000
LIH				0.0000	0.0000	0.0000	0.0000
NH2				0.0000	0.0000	0.0000	0.0000
NH3				0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES							
LI3N/C/				0	0	0	0
LI2O/L/				0.9019	0.9089	1.0104	0
LI2O/SOLID/				0	0	0	0.9885
LI/LIQUID/				0	0	0	0

TABLE 171

[illegible]

TABLE 1.72

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	3542.3	2124.4	1771.8	1510.5
TEMPERATURE (KELVIN)	-97.207	-205.57	-238.20	-267.73
ENTHALPY (KILOCALORIES)	293.04	293.04	293.04	293.04
ENTROPY (CALORIES/DEG.K)	47.431	46.072	45.847	46.792
HEAT CAPACITY (CAL/K)	4.9830	4.3912	4.1064	3.8226
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.1798	0.0085	0.0017	0.0004
LI	0.2157	0.0179	0.0033	0.0006
N	0.0000	0.0000	0.0000	0.0000
F	0.0014	0.0000	0.0000	0.0000
H2	1.0450	1.2535	1.2646	1.2667
HF	0.6001	0.3778	0.3627	0.3600
N2	0.5422	0.5422	0.5422	0.5422
LI2	0.0008	0.0000	0.0000	0.0000
LIH	0.0249	0.0006	0.0000	0.0000
LIF	2.2331	1.8308	1.4094	1.0724
LI2F2	0.0042	0.0353	0.0857	0.1760
LI3F3	0.1367	0.3246	0.4365	0.4042
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI3N/C/	0	0	0	0
LIF/LIQUID/	0	0	0	0.2560
LIF/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

TABLE 173

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	LIH	14.000		0.8200	298.16
	CLF3	86.000		1.810	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	LIH	LIH	-21.600		
	CLF3	CLF3	-44.400		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	1.7614			
	LI	1.7614			
	F	2.7905			
	CL	0.9302			
	PROPELLANT ENTHALPY	-79.346	KCAL/100 GM		
	PROPELLANT DENSITY	1.548	GM/CC		
	CHAMBER	1000.0	EXHAUST		
	EXHAUST	14.70			
	PRESSURE (PSI)			0.0559	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	0.2000
	ISP (SEC)			325.73	355.04
	IVSP(LB-SEC/CU IN)			18.221	19.861
	TEMPERATURE (K)	4167.5		1697.2	1435.2
	CP (CAL/GM-DEG.K)	0.33611		0.31352	0.32341
	MOL. WT.-EFFECTIVE	25.972		29.802	32.148
	CP/CV -EFFECTIVE	1.2947		1.2702	1.2363
	CF -APPROX.			1.8383	2.0037
	PEAF/M (SEC)			15.116	10.872
	AE/AT -APPROX.			42.655	306.78
	FROZEN EQUILIBRIA				
	ISP (SEC)			307.41	324.01
	TEMPERATURE (K)	4167.5		818.96	399.38
	C* (FT/SEC)	5701.0			
	CF (SEC)			1.7349	1.8286
	PEAF/M (SEC)			8.8682	4.1032
	AE/AT			25.024	115.78

TABLE 174

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4187.5	2114.4	1697.2	1435.2
TEMPERATURE (KELVIN)	-79.346	-175.32	-201.28	-224.22
ENTHALPY (KILOCALORIES)	230.06	230.06	230.06	230.06
ENTROPY (CALORIES/DEG.K)	33.611	31.744	31.352	32.341
HEAT CAPACITY (CAL/K)	3.8502	3.5795	3.3555	3.1106
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0883	0.0000	0.0000	0.0000
LI	0.0211	0.0000	0.0000	0.0000
F	0.1281	0.0064	0.0010	0.0002
CL	0.2360	0.1688	0.1269	0.0894
H2	0.0293	0.0000	0.0000	0.0000
HCL	0.1375	0.0501	0.0366	0.0303
HF	1.4766	1.7113	1.7249	1.7311
CLF	0.0005	0.0006	0.0004	0.0001
LI2	0.0000	0.0000	0.0000	0.0000
LIH	0.0004	0.0000	0.0000	0.0000
LICL	0.5544	0.6885	0.6961	0.7012
LI2CL2	0.0001	0.0003	0.0006	0.0006
LIF	1.1729	0.6726	0.5503	0.3252
LI2F2	0.0003	0.0106	0.0388	0.0691
LI3F3	0.0039	0.0594	0.1454	0.1094
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0007	0.0107	0.0345	0.0539
CONDENSED PHASES				
LICL/L/	0	0	0	0
LIF/LIQUID/	0	0	0	0.2674
LIF/SOLID/	0	0	0	0
LI/LIQUID/	0	0	0	0

673

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLO3F	70.000		1.430	298.16
	LIH	30.000		0.8200	293.16
	INGREDIENT DATA:		HEAT OF FORM.		
	CLO3F		-10.100		
	LIH		-21.600		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	3.7745			
	LI	3.7745			
	O	2.0436			
	F	0.6832			
	CL	0.6832			
	PROPELLANT ENTHALPY	-88.430	KCAL/100 GM		
	PROPELLANT DENSITY	1.169	GM/CC		
	CHAMBER	1000.0	EXHAUST	2.000	0.0422 LB/CU IN
	PRESSURE (PSI)				EXHAUST
	SHIFTING EQUILIBRIA				0.2000
	ISP (SEC)				
	IVSP(LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)	3057.6			
	MOL. WT.-EFFECTIVE	0.55092			
	CP/CV -EFFECTIVE	24.956			
	CF -APPROX.	1.1690			
	PEAF/M (SEC)				
	AE/AT -APPROX.				
	FROZEN EQUILIBRIA				
	ISP (SEC)				
	TEMPERATURE (K)				
	C* (FT/SEC)	3057.6			
	CF	5154.4			
	PEAF/M (SEC)				
	AE/AT				

TABLE 176

CASE BASIS: 100 GM PROPELLANT					
		CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)		1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)		3057.6	2047.6	1759.4	1555.8
ENTHALPY (KILOCALORIES)		-88.430	-168.88	-195.77	-222.44
ENTROPY (CALORIES/DEG.K)		280.28	280.28	280.28	280.28
HEAT CAPACITY (CAL/K)		55.092	55.648	56.129	56.294
MOLES OF GAS		4.0070	3.6572	3.4939	3.4655
MOLECULAR COMPOSITION:					
H		0.0418	0.0042	0.0013	0.0006
LI		0.2801	0.1000	0.0452	0.0326
O		0.0003	0.0000	0.0000	0.0000
F		0.0000	0.0000	0.0000	0.0000
CL		0.0001	0.0000	0.0000	0.0000
H2		0.8487	0.9866	1.0178	1.0249
H2O		0.4939	0.3150	0.5734	0.6123
HCL		0.0036	0.0004	0.0002	0.0001
HF		0.0292	0.0106	0.0075	0.0057
O2		0.0001	0.0000	0.0000	0.0000
OH		0.0088	0.0002	0.0000	0.0000
F2		0.0000	0.0000	0.0000	0.0000
CL2		0.0000	0.0000	0.0000	0.0000
CLO		0.0000	0.0000	0.0000	0.0000
CLF		0.0000	0.0000	0.0000	0.0000
LI2		0.0032	0.0001	0.0000	0.0000
LIH		0.0382	0.0033	0.0005	0.0002
LI2CL2		0.6773	0.6818	0.6823	0.6828
LI2CL		0.0011	0.0005	0.0003	0.0002
LI2F		0.5578	0.5578	0.5267	0.5677
LI2F3		0.0015	0.0074	0.0162	0.0235
LI2O		0.0310	0.0334	0.0389	0.0209
LI2O		0.0010	0.0000	0.0000	0.0000
LI2O		0.0189	0.0032	0.0009	0.0004
LI2O2		0.0027	0.0002	0.0000	0.0000
LI2O4		0.0673	0.7524	0.5823	0.4935
LI2O2H2		0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES					
LI2O/L		0	0	0	0
LI2O/LIQUID/		0	0	0	0
LI2O/SOLID/		0	0	0	0
LI2O/LIQUID/		0.5536	0.7783	0.8928	0.9434
LI2O/SOLID/		0	0	0	0
LI2O/LIQUID/		0	0	0	0

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																														</
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TABLE 178

CASE BASIS: 100 G4 PROPELLANT							
	CHAMBER	EXHAUST	EXHAUST	EXHAUST	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)	1000.0	14.70	2193.7	2.000	1863.7	0.2000	0.2000
TEMPERATURE (KELVIN)	3278.8	2193.7	1863.7	0.0000	1863.7	1663.9	1663.9
ENTHALPY (KILOCALORIES)	-69.362	-146.03	-146.03	0.0000	-171.91	-196.75	-196.75
ENTROPY (CALORIES/DEG.K)	269.31	269.31	269.31	0.0000	269.31	269.31	269.31
HEAT CAPACITY (CAL/K)	54.330	53.262	53.262	0.0000	53.262	53.843	53.843
MOLES OF GAS	3.4746	3.2847	3.2847	0.0000	3.1426	3.1157	3.1157
MOLECULAR COMPOSITION:							
H	0.0286	0.0031	0.0031	0.0011	0.0011	0.0005	0.0005
LI	0.1527	0.0667	0.0667	0.0094	0.0094	0.0335	0.0335
N	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O	0.0086	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000
CL	0.0034	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2	0.1346	0.1024	0.1024	0.1156	0.1156	0.1181	0.1181
H2O	0.7664	0.8397	0.8397	0.9335	0.9335	0.9514	0.9514
HCL	0.0038	0.0004	0.0004	0.0002	0.0002	0.0001	0.0001
O2	0.0200	0.0003	0.0003	0.0000	0.0000	0.0000	0.0000
OH	0.0692	0.0036	0.0036	0.0007	0.0007	0.0002	0.0002
N2	0.2451	0.2503	0.2503	0.2509	0.2509	0.2509	0.2509
NO	0.0116	0.0003	0.0003	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ClO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LI2	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LIH	0.4967	0.5011	0.5011	0.5015	0.5015	0.5017	0.5017
LI2CL2	0.0004	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
LI2O	0.0031	0.0004	0.0004	0.0000	0.0000	0.0000	0.0000
LI2C	0.0341	0.0100	0.0100	0.0038	0.0038	0.0020	0.0020
LI2OH	1.4848	1.5049	1.5049	1.2963	1.2963	1.2570	1.2570
LI2H2H2	0.0002	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
NH3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES							
LI2N/C/	0	0	0	0	0	0	0
LI2CL/L/	0	0	0	0	0	0	0
LI2C/L/	0.0876	0.6513	0.6513	0.7763	0.7763	0.8002	0.8002
LI2C/SOLID/	0	0	0	0	0	0	0
LI/LIQUID/	0	0	0	0	0	0	0

TABLE 179

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	LIH	25.000		0.8200	298.16
	NH ₄ ClO ₄	75.000		1.960	298.16
INGREDIENT DATA:					
	LIH		HEAT OF FORM.		
	NH ₄ ClO ₄		-21.600		
			-69.420		
ATOMIC COMPOSITION (GM AT/100GM)					
	H	5.6987			
	LI	3.1454			
	N	0.6383			
	O	2.5532			
	CL	0.6383			
PROPELLANT ENTHALPY					
		-112.25	KCAL/100 GM		
PROPELLANT DENSITY					
		1.454	GM/CC		
		CHAMBER			
		1000.0			
PRESSURE (PSI)					
SHIFTING EQUILIBRIA					
	ISP (SEC)			0.0526	LB/CU IN
	IVSP (LB-SEC/CU IN)			EXHAUST	EXHAUST
	TEMPERATURE (K)			2.000	0.2000
	CP (CAL/GM-DEG.K)	2524.8		287.49	322.57
	MOL. WT.-EFFECTIVE	0.65176		15.106	16.951
	CP/CV -EFFECTIVE	24.290		1535.7	1251.3
	CF -APPROX.	1.1435		0.64283	0.61725
	PEAF/M (SEC)			25.659	26.204
	AE/AT -APPROX.			1.1370	1.1401
FROZEN EQUILIBRIA					
	ISP (SEC)			1.9328	2.1686
	TEMPERATURE (K)			17.999	12.799
	C* (FT/SEC)			60.505	430.25
	CF			279.06	305.85
	PEAE/M (SEC)			1104.1	795.45
	AE/AT			1.6761	2.0562
		2524.8		14.093	9.2572
		4765.6		47.341	311.18

TABLE 180

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GR PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	2524.8	1693.8	1535.7	1251.3
TEMPERATURE (KELVIN)	-112.25	-181.61	-207.24	-231.83
ENTHALPY (KILOCALORIES)	283.60	283.60	283.60	283.60
ENTROPY (CALORIES/DEG.K)	65.176	64.651	64.283	61.725
HEAT CAPACITY (CAL/K)	4.1169	3.9203	3.6973	3.5162
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0085	0.0003	0.0002	0.0000
LI	0.0300	0.0029	0.0020	0.0001
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
CL	0.0000	0.0000	0.0000	0.0000
H2	1.5239	1.5473	1.5485	1.5496
H2O	1.0387	1.1870	1.2105	1.2866
HC..	0.0044	0.0006	0.0003	0.0003
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0013	0.0000	0.0000	0.0000
N2	0.3190	0.3192	0.3192	0.3192
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
ClO	0.0000	0.0000	0.0000	0.0000
Li2	0.0001	0.0000	0.0000	0.0000
LiH	0.0069	0.0002	0.0000	0.0000
LiCl	0.6264	0.6315	0.6349	0.6310
Li2CL2	0.0036	0.0031	0.0015	0.0035
LiO	0.0000	0.0000	0.0000	0.0000
Li2O	0.0017	0.0000	0.0000	0.0000
LiOH	0.5516	0.2275	0.1800	0.0259
Li2C2H2	0.0002	0.0001	0.0000	0.0000
NH	0.0000	0.0000	0.0000	0.0000
NH2	0.0000	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES				
LI3P/C/	0	0	0	0
Li2L/L/	0	0	0	0
Li4P/L/	0.9595	0.9578	0	0
LI2O/SOLID/	0	0.1807	1.1626	1.2807
LI/LIQUID/	0	0	0	0

TABLE 181

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	MGH2	69.000		1.450	298.16
	O2	31.000		1.142	90.200
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
MGH2	NGH2	-17.000			
O2	O2	-3.0800			
ATOMIC COMPOSITION(GM AT/100GM)					
H		5.2400			
O		1.9375			
MG		2.6200			
PROPELLANT ENTHALPY		-47.524	KCAL/100 GM		
PROPELLANT DENSITY		1.338	GM/CC		
	CHAMBER		EXHAUST		
	1000.00		14.70		
PRESSURE (PSI)				0.0483	LB/CU IN
SHIFTING EQUILIBRIA				EXHAUST	EXHAUST
ISP (SEC)				2.000	0.2000
IVSP(LB-SEC/CU IN)				316.20	354.15
TEMPERATURE (K)				15.297	17.122
CP (CAL/GM-DEG.K)				2145.1	1685.0
MOL. WT.-EFFECTIVE				0.51780	0.49282
CP/CV -EFFECTIVE				29.879	30.266
CF -APPROX.				1.1474	1.1537
PEAE/M (SEC)				2.0788	2.3282
AE/AT -APPROX.				19.630	13.591
FROZEN EQUILIBRIA				64.526	446.76
ISP (SEC)				282.51	310.03
TEMPERATURE (K)				1253.9	860.33
C* (FT/SEC)					
CF (SEC)					
PEAE/M (SEC)				1.8573	2.0382
AE/AT				13.679	8.5521
				44.964	281.12

TABLE 183

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	NGH2	24.000		1.450	298.16
	F2	76.000		1.510	85.200
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
NGH2	MGH2	-17.000			
F2	F2	-3.4670			
ATOMIC COMPOSITION(GM AT/100GM)					
H		1.8226			
F		4.0000			
MG		0.9113			
PROPELLANT ENTHALPY					
		-22.426 KCAL/100 GM			
PROPELLANT DENSITY					
		1.495 GM/CC			
PRESSURE (PSI)					
		CHAMBER	EXHAUST	0.0540 LB/CU IN	0.2000
		1000.0	14.70	2.000	
SHIFTING EQUILIBRIA					
ISP (SEC)				377.02	414.36
IVSP(LB-SEC/CU IN)				20.367	22.384
TEMPERATURE (K)				2884.8	2008.7
CP (CAL/GM-DEG.K)		4992.6		0.31060	0.30547
MOL. WT.-EFFECTIVE		0.32593		32.114	32.919
CP/CV -EFFECTIVE		26.289		1.2488	1.2463
CF -APPROX.		1.3020		1.9643	2.1589
PEAF/M (SEC)				20.599	12.732
AE/AT -APPROX.				53.662	331.67
FROZEN EQUILIBRIA					
ISP (SEC)				330.18	348.62
TEMPERATURE (K)				992.20	481.15
C* (FT/SEC)		4992.6			
CF (SEC)		6175.3			
PEAF/M (SEC)				1.7203	1.8164
AE/AT				9.8828	4.5390
				25.745	118.24

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000
4992.6	3456.1	2884.8	2008.7
-22.426	-145.60	-185.79	-219.75
223.11	223.11	223.11	223.11
32.593	31.490	31.060	30.547
3.8039	3.2769	3.1139	3.0378
0.1822	0.0381	0.0064	0.0000
1.0864	0.5446	0.3801	0.3548
0.1115	0.0368	0.0033	0.0000
0.0147	0.0016	0.0002	0.0000
1.6090	1.7814	1.8159	1.8226
0.0019	0.0000	0.0000	0.0000
0.2917	0.0749	0.0120	0.0000
0.5062	0.7995	0.0960	0.8603
0.0002	0.0000	0.0000	0.0000
0	0	0	0
0	0	0	0.0509
0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
F
MG
H2
HF
MGH
MGF
MGF2
F2

CONDENSED PHASES
MGF2/C/
MGF2/L/
MG/LIQUID/

TABLE 185

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	MGH2	33.000		1.450	293.16
	OF2	67.000		1.530	128.00
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	MGH2		-17.000		
	OF2		3.6000		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	2.5061			
	O	1.2407			
	F	2.4815			
	MG	1.2530			
	PROPELLANT ENTHALPY		KCAL/100 GM		
	PROPELLANT DENSITY		CM/CC		
		-16.835			
		1.503			
		CHAMBER			
		1000.0			
	PRESSURE (PSI)			0.0543	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	EXHAUST
	ISP (SEC)			2.000	0.2000
	IVSP(LB-SEC/CU IN)			351.82	394.06
	TEMPERATURE (K)			19.100	21.394
	CP (CAL/GM-DEG.K)			2747.0	2465.8
	MOL. WT.-EFFECTIVE	4371.6		0.35819	0.36469
	CP/CV -EFFECTIVE	0.35387		32.068	33.757
	CF -APPROX.	26.949		1.2092	1.1925
	PEAF/M (SEC)	1.2632		1.9623	2.1979
	AE/AT -APPROX.			21.051	16.027
	FROZEN EQUILIBRIA			58.706	446.95
	ISP (SEC)			312.58	331.16
	TEMPERATURE (K)			1024.2	559.14
	C* (FT/SEC)	4371.6			
	CF	5768.5			
	PEAF/M (SEC)			1.7434	1.8470
	AE/AT			10.512	5.4169
				29.315	151.07

TABLE 186

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4371.6	3039.1	2747.0	2465.8
TEMPERATURE (KELVIN)	-16.835	-122.51	-159.09	-195.30
ENTHALPY (KILOCALORIES)	232.02	232.02	232.02	232.02
ENTROPY (CALORIES/DEG.K)	35.387	34.766	35.819	36.469
HEAT CAPACITY (CAL/K)	3.7108	3.2731	3.1184	2.9624
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.1917	0.0546	0.0610	0.0538
O	0.2538	0.0933	0.0758	0.0569
F	0.1083	0.0156	0.0109	0.0069
MG	0.2279	0.1800	0.1833	0.1712
H2	0.0819	0.0406	0.0357	0.0286
H2O	0.1187	0.1782	0.1564	0.1260
HF	1.3597	1.4952	1.7229	1.9516
O2	0.1451	0.1615	0.1320	0.1010
OH	0.1985	0.0976	0.0714	0.0466
F2	0.0000	0.0000	0.0000	0.0000
MGH	0.0087	0.0005	0.0002	0.0000
MGF	0.2604	0.0771	0.0452	0.0221
MGF2	0.3765	0.4468	0.3512	0.2504
MGO	0.0332	0.0115	0.0060	0.0025
MGOH	0.3464	0.4104	0.2654	0.1447
CONDENSED PHASES				
MGO/C/	0	0.1267	0.4007	0.6621
MGF2/C/	0	0	0	0
MGO2H2/C/	0	0	0	0
MGO/L/	0	0	0	0
MGF2/L/	0	0	0	0
MGO/LIQUID/	0	0	0	0

TABLE 187

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	MGH2	61.000		1.450	298.16
	H2O2	39.000		1.443	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	MGH2		-17.000		
	H2O2		-44.840		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	6.9255			
	O	2.2930			
	MG	2.3162			
	PROPELLANT ENTHALPY	-90.786	KCAL/100 GM		
	PROPELLANT DENSITY	1.447	GM/CC		
	CHAMBER	EXHAUST			
	1000.0	14.70			
	PRESSURE (PSI)				
	SHIFTING EQUILIBRIA				
	ISP (SEC)				
	IVSP(LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)				
	MOL. WT.-EFFECTIVE				
	CP/CV -EFFECTIVE				
	CF -APPROX.				
	PEAE/M (SEC)				
	AE/AT -APPROX.				
	FROZEN EQUILIBRIA				
	ISP (SEC)				
	TEMPERATURE (K)				
	C* (FT/SEC)				
	CF (SEC)				
	PEAE/M (SEC)				
	AE/AT				

TABLE 188

CASE
BASIS: 100 GM PROPELLANT

CHAMBER	EXHAUST	EXHAUST	EXHAUST	EXHAUST
1000.0	14.70	2.000	0.2000	0.2000
3073.1	2420.1	2145.1	1815.7	1815.7
-90.786	-180.62	-213.87	-246.19	-246.19
247.20	247.20	247.20	247.20	247.20
60.998	60.886	60.023	58.215	58.215
4.0063	3.7403	3.6148	3.5117	3.5117
0.0810	0.0604	0.0384	0.0121	0.0121
0.0000	0.0000	0.0000	0.0000	0.0000
0.2159	0.1714	0.1084	0.0404	0.0404
2.9077	3.2059	3.3333	3.4369	3.4369
0.2276	0.1508	0.0857	0.0173	0.0173
0.0000	0.0000	0.0000	0.0000	0.0000
0.0023	0.0006	0.0001	0.0000	0.0000
0.0373	0.0031	0.0007	0.0001	0.0001
0.0003	0.0000	0.0000	0.0000	0.0000
0.5341	0.1482	0.0482	0.0048	0.0048
0.9925	1.9935	2.1590	2.2709	2.2709
0	0	0	0	0
0.5362	0	0	0	0
0	0	0	0	0

PRESSURE (PSI)
TEMPERATURE (KELVIN)
ENTHALPY (KILOCALORIES)
ENTROPY (CALORIES/DEG.K)
HEAT CAPACITY (CAL/K)
MOLES OF GAS
MOLECULAR COMPOSITION:

H
O
MG
H2
H2O
O2
OH
MGH
MGO
MGOH

CONDENSED PHASES
MGO/C/
MGO2H2/C/
MGO/L/
MG/LIQUID/

TABLE 189

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	MGH2	64.000		1.450	298.16
	N2O4	36.000		1.430	298.16
INGREDIENT DATA:	MGH2		HEAT OF FORM.		
	N2O4		-17.000		
			-5.4000		
ATOMIC COMPOSITION(GM AT/100GM)					
	H	4.8603			
	N	0.7825			
	O	1.5649			
	MG	2.4301			
PROPELLANT ENTHALPY		-43.425	KCAL/100 GM		
PROPELLANT DENSITY		1.443	GM/CC		
		CHAMBER	EXHAUST	0.0521 LB/CU IN	
		1000.0	14.70	EXHAUST	0.2000
PRESSURE (PSI)				298.45	328.30
SHIFTING EQUILIBRIA				15.557	17.113
ISP (SEC)				1438.7	1228.7
IVSP(LB-SEC/CU IN)				0.45898	0.45450
TEMPERATURE (K)		2957.3		27.135	28.901
CP (CAL/GM-DEG.K)		0.51371		1.1898	1.1782
MOL. WT.-EFFECTIVE		26.208		1.9437	2.1381
CP/CV -EFFECTIVE		1.1732		15.359	11.196
CF -APPROX.				50.015	364.58
PEAC/M (SEC)				283.40	303.60
AE/AT -APPROX.				999.08	582.11
FROZEN EQUILIBRIA					
ISP (SEC)				1.8457	2.0098
TEMPERATURE (K)		2957.3		11.630	6.2226
C* (FT/SEC)		4940.2		37.870	202.63
CF (SEC)					
PEAC/M (SEC)					
AE/AT					

TABLE 190

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2957.3	1950.5	1438.7	1228.7
ENTHALPY (KILOCALORIES)	-43.425	-121.17	-145.79	-167.29
ENTROPY (CALORIES/DEG.K)	220.93	220.93	220.93	220.93
HEAT CAPACITY (CAL/K)	51.371	48.647	45.898	45.450
MOLES OF GAS	3.8156	3.6842	3.6853	3.4600
MOLECULAR COMPOSITION:				
H	0.0482	0.0034	0.0001	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
MG	0.7731	0.8546	0.8626	0.6950
H2	2.1865	2.4219	2.4288	2.4299
H2O	0.0226	0.0001	0.0000	0.0000
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
N2	0.3912	0.3912	0.3912	0.3347
NO	0.0000	0.0000	0.0000	0.0000
MGH	0.1148	0.0106	0.0025	0.0005
MGO	0.0001	0.0000	0.0000	0.0000
MGOH	0.2788	0.0023	0.0000	0.0000
CONDENSED PHASES				
MGO/C/	1.2632	1.5626	1.5649	1.5649
MG3H2/C/	0	0	0	0.0566
MG02H2/C/	0	0	0	0
MGO/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 191

CASE	PROPELLANT COMPOSITION	WEIGHTS	MOLAR	DENSITY	REF. TEMP.
	MGH2	24.000		1.450	298.16
	NF3	76.000		1.532	144.00
INGREDIENT DATA:					
	MGH2		HEAT OF FORM.		
	NF3		-17.000		
ATOMIC COMPOSITION (GM AT/100GM)					
	H	1.8226			
	N	1.0703			
	F	3.2109			
	MG	0.9113			
PROPELLANT ENTHALPY					
		-49.742	KCAL/100 GM		
PROPELLANT DENSITY					
		1.511	GM/CC		
CHAMBER					
		1000.0			
PRESSURE (PSI)					
			EXHAUST	0.0546	LB/CU IN
SHIFTING EQUILIBRIA					
	ISP (SEC)		2.000	EXHAUST	0.2000
	IVSP (LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)				
	MOL. WT.-EFFECTIVE				
	CP/CV -EFFECTIVE				
	CF -APPROX.				
	PEAE/M (SEC)				
	AE/AT -APPROX.				
FROZEN EQUILIBRIA					
	ISP (SEC)				
	TEMPERATURE (K)				
	C* (FT/SEC)				
	CF (SEC)				
	PEAE/M (SEC)				
	AE/AT				

TABLE 192

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4579.9	2816.7	2282.1	1961.9
TEMPERATURE (KELVIN)	-49.742	-153.86	-185.05	-213.24
ENTHALPY (KILOCALORIES)	217.93	217.93	217.93	217.93
ENTROPY (CALORIES/DEG.K)	33.238	31.904	32.361	33.635
HEAT CAPACITY (CAL/K)	3.5461	3.2199	3.0393	2.7941
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.1584	0.0359	0.0140	0.0069
N	0.0019	0.0000	0.0000	0.0000
F	0.3120	0.0048	0.0002	0.0000
MG	0.1273	0.1182	0.0877	0.0616
H2	0.0327	0.0536	0.1135	0.1495
HF	1.5955	1.6791	1.5814	1.5167
N2	0.5342	0.5351	0.5352	0.5352
MGH	0.0032	0.0003	0.0001	0.0000
MGF	0.2582	0.0585	0.0176	0.0053
MGF2	0.5226	0.7342	0.6896	0.5190
F2	0.0000	0.0000	0.0000	0.0000
CONDENSED PHASES				
MGF2/C/	0	0	0	0
MG3N2/C/	0	0	0	0
MGF2/L/	0	0	0.1163	0.3254
MG/LIQUID/	0	0	0	0

TABLE 193

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	MGH2	18.000		1.450	298.16
	CLF3	82.000		1.810	298.16
	INGREDIENT DATA:	FORMULA	HEAT OF FORM.		
	MGH2		-17.000		
	CLF3		-44.400		
	ATOMIC COMPOSITION(GM AT/100GM)				
	H	1.3670			
	F	2.6607			
	MG	0.6835			
	CL	0.6869			
	PROPELLANT ENTHALPY	-50.997	KCAL/100 GM		
	PROPELLANT DENSITY	1.732	CM/CC		
	CHAMBER	1000.0			
	EXHAUST	14.70			
	PRESSURE (PSI)			0.0626	LB/CU IN
	SHIFTING EQUILIBRIA			EXHAUST	EXHAUST
	ISP (SEC)			2.000	0.2000
	IVSP(LB-SEC/CU IN)			300.53	330.95
	TEMPERATURE (K)			18.813	20.717
	CP (CAL/GM-DEG.K)	4347.3		2164.1	1837.6
	MOL. WT.-EFFECTIVE	0.26791		0.28146	0.29027
	CP/CV -EFFECTIVE	33.609		39.914	42.816
	CF -APPROX.	1.2832		1.2149	1.1903
	PEAF/M (SEC)			1.6876	2.0787
	AE/AT -APPROX.			15.598	11.212
	FROZEN EQUILIBRIA			48.984	352.10
	ISP (SEC)			277.91	293.98
	TEMPERATURE (K)	4347.3		939.77	493.75
	C* (FT/SEC)	5122.5			
	CF				
	PEAF/M (SEC)			1.7456	1.8465
	AE/AT			8.6987	4.3204
				27.318	135.68

TABLE 194

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT	1000.0	14.70	2.000	0.2000
PRESSURE (PSI)	4347.3	2540.1	2164.1	1837.6
TEMPERATURE (KELVIN)	-50.997	-130.70	-154.80	-176.87
ENTHALPY (KILOCALORIES)	182.23	182.23	182.23	182.23
ENTROPY (CALORIES/DEG.K)	26.791	27.076	28.146	29.027
HEAT CAPACITY (CAL/K)	2.9754	2.6877	2.5054	2.3356
MOLES OF GAS				
MOLECULAR COMPOSITION:				
H	0.0350	0.0001	0.0000	0.0000
F	0.3913	0.1139	0.0550	0.0171
MG	0.0098	0.0000	0.0000	0.0000
CL	0.5337	0.6643	0.7069	0.7194
H2	0.0036	0.0000	0.0000	0.0000
HCL	0.0977	0.0312	0.0227	0.0196
HF	1.2268	1.3356	1.3442	1.3473
F2	0.0001	0.0000	0.0000	0.0000
CL2	0.0037	0.0178	0.0259	0.0386
MGH	0.0001	0.0000	0.0000	0.0000
MGCL	0.0029	0.0000	0.0000	0.0000
MGCl2	0.0126	0.0055	0.0038	0.0032
MGF	0.0537	0.0000	0.0000	0.0000
MGF2	0.3843	0.3744	0.2489	0.1261
MGFCL	0.2201	0.1447	0.0979	0.0643
CONDENSED PHASES				
MGF2/C/	0	0	0	0
MGF2/L/	0	0.1588	0.3328	0.4899
MGCL2/C/	0	0	0	0
MGCl2/L/	0	0	0	0
MG/LIQUID/	0	0	0	0

TABLE 195

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	CLO ² F	43.500		1.430	293.16
	MGH ²	56.500		1.450	293.16
INGREDIENT DATA:	FORMULA	HEAT OF FORM.			
CLO ² F		-10.100			
MGH ²		-17.000			
ATOMIC COMPOSITION (GM AT/100GM)					
H		4.2907			
O		1.2737			
F		0.4246			
MG		2.1454			
CL		0.4246			
		-40.759	KCAL/100 GM		
PROPELLANT ENTHALPY		1.441	CM/CC		
PROPELLANT DENSITY				0.0521	LB/CU IN
PRESSURE (PSI)	CHAMBER	EXHAUST	EXHAUST	EXHAUST	EXHAUST
SHIFTING EQUILIBRIA	1000.0	14.70	2.000	0.2000	
ISP (SEC)		260.25	303.32	335.33	
IVSP (LB-SEC/CU IN)		13.552	15.794	17.617	
TEMPERATURE (K)		2381.2	2020.3	1675.2	
CP (CAL/GM-DEG.K)	3101.5	0.44183	0.43254	0.42326	
MOL. WT.-EFFECTIVE	0.43447	30.827	31.790	33.219	
CP/CV -EFFECTIVE	29.350	1.1708	1.1689	1.1646	
CF -APPROX.	1.1846	1.7576	2.0494	2.2849	
PEAF/M (SEC)		25.660	18.114	12.886	
AE/AT -APPROX.		11.792	61.168	435.14	
FROZEN EQUILIBRIA					
ISP (SEC)		237.08	270.46	294.45	
TEMPERATURE (K)		1573.5	1006.6	685.20	
C* (FT/SEC)	3101.5	1.6011	1.8265	1.9886	
CF	4764.0	19.551	11.835	6.8548	
PEAF/M (SEC)		8.9846	39.963	231.47	
AE/AT					

TABLE 196

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
SASIS: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70		
TEMPERATURE (KELVIN)	3101.5	2381.2	2.000	0.2000
ENTHALPY (KILOCALORIES)	-40.759	-116.60	2020.3	1675.2
ENTROPY (CALORIES/DEG.K)	213.20	213.20	-146.49	-172.31
HEAT CAPACITY (CAL/K)	43.447	44.163	213.20	213.20
MOLES OF GAS	3.4072	3.2439	43.254	42.326
MOLECULAR COMPOSITION:			3.1456	3.0103
H	0.0617	0.0361	0.0127	0.0025
O	0.0000	0.0000	0.0000	0.0000
F	0.0000	0.0000	0.0000	0.0000
MG	0.5396	0.6043	0.5600	0.4966
CL	0.0019	0.0009	0.0002	0.0000
H2	1.6808	1.9105	2.0142	2.0928
H2O	0.0506	0.0152	0.0017	0.0000
HCL	0.0930	0.0837	0.0425	0.0139
HF	0.1875	0.2292	0.1901	0.0874
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0007	0.0000	0.0000	0.0000
F2	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
CLF	0.0000	0.0000	0.0000	0.0000
MGH	0.0773	0.0089	0.0026	0.0006
MGCL	0.0105	0.0020	0.0005	0.0001
MGCL2	0.0847	0.0972	0.1040	0.1196
MGF	0.0350	0.0100	0.0044	0.0011
MGF2	0.0262	0.0208	0.0293	0.0238
MGFCL	0.1497	0.1436	0.1735	0.1713
MGO	0.0003	0.0000	0.0000	0.0000
MGOH	0.4075	0.0914	0.0109	0.0005
CONDENSED PHASES				
MGO/C/	0	1.1770	1.2611	1.2731
MGF2/C/	0	0	0	0
MGOH2/C/	0	0	0	0
MGO/L/	0.0146	0	0	0
MGF2/L/	0	0	0	0
MGO2/C/	0	0	0	0
MGO2/L/	0	0	0	0
MGO/LIQUID/	0	0	0	0

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CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR
	MGH2	60.000	
	NO2CLO4	40.000	
INGREDIENT DATA:	MGH2	H*AT OF FORM.	
	NO2CLO4	-17.000	
		8.0000	
ATOMIC COMPOSITION(GM AT/100GM)			
	H	4.5565	
	N	0.2750	
	O	1.6499	
	MG	2.2782	
	CL	0.2750	
PROPELLANT ENTHALPY		-36.530	KCAL/100 GM
PROPELLANT DENSITY		1.684	CM/CC
	CHAMBER		EXHAUST
	1000.0	14.70	
PRESSURE (PSI)			0.0608 LB/CU IN
SHIFTING EQUILIBRIA			EXHAUST
ISP (SEC)			0.2000
IVSP(LB-SEC/CU IN)		262.37	343.97
TEMPERATURE (K)		15.959	20.923
CP (CAL/GM-DEG.K)	3117.6	2464.2	1745.9
MOL. WT.-EFFECTIVE	0.47135	0.47885	0.45441
CP/CV -EFFECTIVE	29.595	30.882	32.676
CF -APPROX.	1.1661	1.1552	1.1545
PEAF/M (SEC)		1.7647	2.3135
AE/AT -APPROX.		26.294	13.429
		12.034	451.62
FROZEN EQUILIBRIA			
ISP (SEC)		239.65	300.41
TEMPERATURE (K)		1661.0	812.42
C* (FT/SEC)	3117.6		
CF	4783.6		
PEAE/M (SEC)		1.6132	2.0205
AE/AT		20.474	7.9003
		9.3704	265.68

TABLE 198

CASE BASIS: 100 GM PROPELLANT				CHAMBER	EXHAUST	EXHAUST	EXHAUST
PRESSURE (PSI)				1000.0	14.71	2.000	0.2000
TEMPERATURE (KELVIN)				3117.6	2464.2	2134.9	1745.9
ENTHALPY (KILOCALORIES)				-36.530	-115.64	-144.81	-172.51
ENTHALPY (CALORIES/DEG.K)				216.75	216.75	216.75	216.75
HEAT CAPACITY (CAL/K)				47.135	47.885	47.245	45.441
MOLES OF GAS				3.3789	3.2382	3.1136	3.0603
MOLECULAR COMPOSITION:							
H				0.0678	0.0554	0.0307	0.0050
N				0.0060	0.0000	0.0000	0.0000
O				0.0000	0.0000	0.0000	0.0000
MG				0.5210	0.5761	0.5430	0.5034
CL				0.0021	0.0017	0.0007	0.0000
H2				1.6671	2.0770	2.1866	2.2614
H2O				0.6623	0.6384	0.6112	0.6002
HCL				0.1008	0.1123	0.0877	0.0260
O2				0.0000	0.0000	0.0000	0.0000
OH				0.0008	0.0002	0.0000	0.0000
N2				0.1374	0.1375	0.1375	0.1375
NO				0.0000	0.0000	0.0000	0.0000
CL2				0.0000	0.0000	0.0000	0.0000
CLO				0.0000	0.0000	0.0000	0.0000
MGH				0.0793	0.0092	0.0029	0.0007
MGCL				0.0104	0.0022	0.0008	0.0001
MGCL2				0.0808	0.0794	0.0929	0.1244
MGO				0.0003	0.0000	0.0000	0.0000
MGOH				0.4485	0.1487	0.0196	0.0015
NH				0.0000	0.0000	0.0000	0.0000
NH2				0.0001	0.0000	0.0000	0.0000
NH3				0.0001	0.0000	0.0000	0.0000
CONDENSED PHASES							
MGO/C/				0	1.4626	1.5991	1.6482
MG3N2/C/				0	0	0	0
MGO2H2/C/				0	0	0	0
MGO/L/				1.1379	0	0	0
MGCL2/C/				0	0	0	0
MGCL2/L/				0	0	0	0
MG/LIQUID/				0	0	0	0

TABLE 199

CASE	PROPELLANT COMPOSITION	WEIGHT%	MOLAR	DENSITY	REF. TEMP.
	MGH2	56.000		1.450	298.16
	NH4CLO4	44.000		1.960	298.16
INGREDIENT DATA:					
	MGH2	FORMULA	HEAT OF FORM.		
	NH4CLO4		-17.000		
	NH4CLO4		-69.420		
ATOMIC COMPOSITION (GM AT/100GM)					
	H	5.7506			
	N	0.3745			
	O	1.4979			
	MG	2.1264			
	CL	0.3745			
PROPELLANT ENTHALPY					
		-62.144	KCAL/100 GM		
PROPELLANT DENSITY					
		1.637	CM/CC		
PRESSURE (PSI)					
	CHAMBER	1000.0			
SHIFTING EQUILIBRIA					
	ISP (SEC)				
	IVSP (LB-SEC/CU IN)				
	TEMPERATURE (K)				
	CP (CAL/GM-DEG.K)				
	MOL. WT.-EFFECTIVE				
	CP/CV -EFFECTIVE				
	CF -APPROX.				
	PEAF/M (SEC)				
	AE/AT -APPROX.				
FROZEN EQUILIBRIA					
	ISP (SEC)				
	TEMPERATURE (K)				
	C* (FT/SEC)				
	CF				
	PEAF/M (SEC)				
	AE/AT				

TABLE 200

CASE	CHAMBER	EXHAUST	EXHAUST	EXHAUST
BASIS: 100 GM PROPELLANT				
PRESSURE (PSI)	1000.0	14.70	2.000	0.2000
TEMPERATURE (KELVIN)	2914.1	1986.5	1501.8	1187.5
ENTHALPY (KILOCALORIES)	-62.144	-140.50	-166.00	-187.76
ENTROPY (KILOCALORIES/DEG.K)	225.14	225.14	225.14	225.14
HEAT CAPACITY (CAL/K)	52.970	50.440	47.689	45.773
MOLES OF GAS	3.6934	3.7046	3.6911	3.5557
MOLECULAR COMPOSITION:				
H	0.0463	0.0048	0.0002	0.0000
N	0.0000	0.0000	0.0000	0.0000
O	0.0000	0.0000	0.0000	0.0000
MG	0.4531	0.4472	0.4404	0.3396
CL	0.0010	0.0000	0.0000	0.0000
H2	2.6019	2.6556	2.6737	2.6752
H2O	0.0352	0.0003	0.0000	0.0000
HCL	0.1036	0.0242	0.0015	0.0001
O2	0.0000	0.0000	0.0000	0.0000
OH	0.0002	0.0000	0.0000	0.0000
N2	0.1871	0.1872	0.1872	0.1534
NO	0.0000	0.0000	0.0000	0.0000
CL2	0.0000	0.0000	0.0000	0.0000
CLO	0.0000	0.0000	0.0000	0.0000
MGN	0.0718	0.0062	0.0015	0.0002
MGO	0.0082	0.0005	0.0000	0.0000
MGO2	0.1308	0.1749	0.1865	0.1872
MGOH	0.0001	0.0000	0.0000	0.0000
MGOH	0.0000	0.0000	0.0000	0.0000
NH3	0.0001	0.0000	0.0000	0.0000
NH3	0.0002	0.0000	0.0000	0.0000
CONDENSED PHASES				
MGO/C/	1.2086	1.4939	1.4979	1.4979
MGO2/C/	0	0	0	0.0338
MGO2H2/C/	0	0	0	0
MGO/L/	0	0	0	0
MGO2/C/	0	0	0	0
MGO2/L/	0	0	0	0
MGO/LIQUID/	0	0	0	0

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LIST OF NOMENCLATURE

- A = cross-sectional area of the nozzle at any general position
 A = a chemical reactant in the general equation of equilibrium
 A' = frontal area of an individual particle in multiphase flow
 A^* = area of the nozzle at the throat, i.e. at Mach 1
 A_e = area of the nozzle at its exit position
 A_{ij} = atoms of the i th element present in the j th exhaust specie
 A_j = a numerical coefficient which relates an incremental change in concentration to an incremental change in free energy
 a = the number of moles of reactant A in the general equation of equilibrium
 a = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
 a' = acceleration of a solid particle during flow through the nozzle
 a_1 = mass fraction of the gas phase in multiphase flow
 a_2 = mass fraction of the condensed phase in multiphase flow
 a_{ij} = a coefficient which relates the amount of an exhaust specie present to the maximum amount which could theoretically exist, according to the mass balance
- B = a chemical reactant in the general equation of equilibrium
 B_j = the maximum number of moles of a given specie which can theoretically exist for a given propellant composition
 B_0 = the maximum total moles of gas which can theoretically exist for a given propellant composition
 B_j = a numerical coefficient which relates an incremental change in concentration to one in free energy
 b = the number of moles of reactant B in the general equation of equilibrium
 b = an arbitrary parameter proportional to boost velocity
 b = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
- C = a chemical product of combustion in the general equation of equilibrium
 C_j = a numerical coefficient which relates an incremental change in concentration to one in free energy
 C_D = drag coefficient
 c = the number of moles of product C in the general equation of equilibrium
 c = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
 c = velocity of pressure wave propagation
 c^* = characteristic exhaust velocity, or the velocity of sound at the nozzle throat
 c_T = thrust coefficient
 c_p = specific heat capacity at constant pressure
 c_v = specific heat capacity at constant volume
 c_w = discharge coefficient
 c_{vg} = constant volume specific heat capacity of the gas phase in multiphase flow
 c_{pg} = constant pressure specific heat capacity of the gas phase in multiphase flow
 c_{p2} = constant pressure specific heat capacity of the condensed phase in multiphase flow
 cp_1 = constant pressure specific heat capacity of a newly-formed condensed phase, either solid or liquid

D = a chemical product of combustion in the general equation of equilibrium
 D = substantial derivative
 d = the number of moles of product D in the general equation of equilibrium
 d = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
 d = standard derivative

E = internal energy of the system
 E = a chemical product of combustion in the general equation of equilibrium
 E' = energy emitted from an individual condensed particle by radiation
 E_i = total gram-atoms of the i th element present in a given propellant formulation
 e = the number of moles of product E in the general equation of equilibrium
 e = an empirical coefficient relating enthalpy, entropy, and heat capacity to temperature
 e = base of natural logarithms

F = Gibbs' free energy of the system
 F = a chemical product of combustion in the general equation of equilibrium
 F^0 = ideal free energy at 1 atm pressure
 F^* = thrust
 F_i = field forces
 F_p = force acting on an individual condensed particle in multiphase flow
 f = the number of moles of product F in the general equation of equilibrium
 f = mass ratio of condensed species to gas species in multiphase flow

g = acceleration of gravity (32.174 ft/sec^2)
 g^* = local acceleration of gravity

H = enthalpy of the system
 H' = reference enthalpy at a reference temperature
 H_0 = stagnation enthalpy of the system
 H_c = enthalpy of the combustion products in the chamber
 H_e = enthalpy of the combustion products at the nozzle exit
 H_j = enthalpy of the j th specie
 ΔH_v = molar latent heat of phase change
 $\Delta H_{f,j}$ = heat-of-formation of the j th component at a standard reference temperature
 h = average heat transfer coefficient
 h_{bo} = height of a missile at time of burnout

I = total impulse, lb-sec
 I_{sp} = specific impulse, lb-sec/lb
 I_{vap} = volumetric specific impulse
 i = designation for any element in a propellant formulation

J = mechanical equivalent of heat
 j = designation for any product of combustion

K = thermodynamic equilibrium constant
 K' = empirical constant
 K_p = thermodynamic equilibrium pressure constant
 K_n = thermodynamic equilibrium concentration constant
 \bar{k} = mean ratio of specific heat capacities, C_p/C_v , at any general time
 \bar{k} = mean specific heat ratio during nozzle expansion

\ln = natural logarithm to the base $e = 2.718$

M = Mach number

M_j = moles of a given specie j at any general time

M_0 = total moles of gas existing at any general time

MW = mean molecular weight of the combustion products

MW^* = mean molecular weight of the combustion products at the throat, i.e. at Mach 1

m = mass rate of flow

m = designation for any gaseous element in the products of combustion

m' = mass of an individual condensed particle in multiphase flow

$n_A, n_B, n_C, \dots, n_j$ = molar equilibrium concentrations of the respective species in the general equation of equilibrium

n_T = total moles of gas

n_g = moles of gas in multiphase flow

n_g = designation for any gaseous molecule in the products of combustion

n_j = moles of the j th specie

$n_{T_{max}}$ = maximum possible moles of gas which can theoretically be formed from a given propellant composition

Δn = total moles of products minus total moles of reactants

x = distance of nozzle cross-section at any general position

p = pressure

p = designation for any condensed phase in the products of combustion

p_a = external pressure of the surrounding fluid medium

p_c = pressure in the combustion chamber

p_e = pressure of the combustion products at the nozzle exit

p_0 = stagnation pressure of the fluid ($p_0 = p_e$)

p^* = pressure at the throat of the nozzle, i.e. at Mach 1

p_x = total pressure at any given position

p_j = partial pressure of the j th specie

W = work of expansion

$p_A, p_B, p_C, \dots, p_j$ = equilibrium partial pressures of the combustion products in the general equation of equilibrium

q = energy absorbed by the system from its surroundings

q' = total heat transferred between the gas and condensed phases in multiphase flow

q_r = reversible energy change at constant temperature

R = universal gas constant

Re = Reynolds' number

$R = R/MW$

r = radius of an individual condensed particle in multiphase flow

S = absolute entropy of the system
 S^* = ideal entropy at 1 atm pressure
 S' = reference entropy at a reference temperature and 1 atm pressure
 S_j = entropy of the j th specie
 S_{LC} = horizontal distance of a missile from its launching position at time of burnout
 a = empirical constant dependent upon missile design conditions

T = temperature of the system
 T_0 = stagnation temperature of the system
 T_c = combustion or chamber temperature ($T_c = T_0$)
 T_e = temperature of the products of combustion at the nozzle exit
 T^* = temperature of the system at the nozzle throat, i.e. at Mach 1
 T_g = temperature of the gas phase in multiphase flow
 T_s = temperature of the condensed phase in multiphase flow
 t = time

\underline{U} = unit tensor

V = volume of the fluid system at any general time
 V' = specific volume of fluid system
 V_g = specific volume of the gas phase in multiphase flow
 V_p = volume of propellant in a missile
 \underline{v}_0 = velocity vector of the fluid system
 v = fluid velocity at any general position
 v' = effective exhaust velocity
 v_e = velocity of the products of combustion at the nozzle exit
 v^* = fluid velocity at the nozzle throat, i.e. at Mach 1
 v_{max} = maximum attainable exhaust velocity
 v_x = one-dimensional contribution to fluid velocity ($v_x = v$ for unidirectional flow)
 v_g = velocity of the gas phase in multiphase flow
 v_s = velocity of the condensed phase in multiphase flow
 v_{g0} = velocity of the gas phase at the instant a condensed particle enters the gas stream
 v_b = incremental boost velocity imparted to a missile

W_f = mass of missile hardware, or the total mass of a missile at burnout
 W_i = total initial mass of the missile hardware and its propellant
 W_m = total mass of the missile ($W_m = W_i$)
 W_p = total mass of propellant consumed during combustion in time t
 W_o = non-expansion work done by the system
 w = work done by the system on its surroundings

x = linear distance along the nozzle axis
 x = general concentration of a specie in the products of combustion
 x_j = the ratio of the moles of specie j in the combustion products to the total possible moles of specie j which could theoretically be formed
 x_0 = the ratio of the total moles of gas in the combustion products to the total possible moles of gas which could theoretically be formed

γ = general mathematical representation of the free energy of mixing and pressure as a function of concentration
 γ = empirical coefficient dependent upon physical conditions of the system and surrounding, e.g. missile surface area, density of surrounding medium, etc.
 Z = potential energy of position
 α = half-angle of nozzle divergence
 ρ = density of the fluid system or of the propellant
 ρ_0 = stagnation density of the fluid system
 ρ^* = density of the fluid system at the nozzle throat, i.e. at Mach 1
 ρ_g = density of the gas phase in multiphase flow
 ρ_s = density of the condensed phase in multiphase flow
 μ = fluid viscosity
 μ_g = viscosity of the gas phase in multiphase flow
 ϕ = mean ratio of the specific heat capacities, C_p/C_v , for multiphase flow
 ∇ = vector operator
 Δ = incremental change in a property
 σ = Stefan-Boltzmann constant
 ϵ = emissivity constant
 β = angle of missile trajectory with the horizontal
 ∂ = partial derivative
 η = ideal cycle efficiency
 $\pi = 3.1416$